



School of Architecture, Technology and Engineering

Investigation into the effect of rotation on water rockets

Lydia Beniken

XE636

Supervised by: Dr. Derek Covill

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DISCLAIMER

I hereby certify that the attached report is my own work except where otherwise indicated. I have identified my sources of information; in particular I have put in quotation marks any passages that have been quoted word-for-word and identified their origins.

Signed: Lydia Beniken

Date: 26/04/2022

ABSTRACT

Water rockets are very popular, easy to make and have been repeatedly used as learning tools for youngsters. This report aimed to investigate the effect of rotation on water rockets through the design and the testing of two rockets: A red rocket 'Vortex' was designed to rotate by reason of its aerodynamic properties and a blue rocket 'Ctrl' was designed to match the mass and the geometry of Vortex. Except the latter did not allow any rotation and was hence used as a control for comparison against Vortex. Several tools were used to assess the rockets. First, SOLIDWORKS® was used to evaluate the position of the centre of pressure of the rockets. Additionally, Wind tunnel tests were run to estimate the drag coefficient of both rockets and measure the angular velocities of Vortex for different airflow speeds. Finally, A video analysis of the rockets was conducted using Tracker® to identify the max height, velocities and distance travelled. In addition to outlining the trajectory of each rocket.

AKNOWLEDGEMENT

I would like to thank Dr. Derek Covill for providing guidance throughout the whole course. I also would also like to thank Tony Brown a technician at the University of Brighton for their help with the use of different tools crucial to the development and the testing of the rockets. Finally, I would like to thank Toby Wilkinson, another MEng student at the University of Brighton for his support.

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Table of abbreviations:

Abbreviation or Nomenclature	Detailed factor with unit if applicable
NPL	National Physical Laboratory
BS ISO	British Standard International Organization for Standardization
CG	Centre of gravity
CP	Centre of pressure
SM	Stability margin
amb	Ambient
Cd	Coefficient of drag
Re	Reynolds Number
PET	Polyethylene terephthalate
Qty	Quantity
UCL	Upper Control Limit
LCL	Lower Control Limit
\bar{x}	Mean
σ	Standard deviation
x_i	Observed value from data set
MDF	Medium Density Fibreboard
LDF	Light Density Fibreboard
Avg	Average

Symbol/Name	Units	Description
Vf	Metre per second: [m s ⁻¹]	Air flow velocity
μ	Kilogram per metre second: [kg m ⁻¹ s ⁻¹]	Dynamic viscosity
ρ	Kilogram per cubic metre: [kg m ⁻³]	Density
R	Joule per kilogram Kelvin: [J kg ⁻¹ K ⁻¹]	Gas constant
T	Degree Celsius: [°C] Degree Kelvin: [°K]	Temperature
P	Pascals: [Pa] Millimetres of mercury: [mm Hg]	Pressure
Fd	Newtons: N or kilogram metre per square second: [kg m s ⁻²]	Drag force
h	Metre: [m]	Height
A	Square metre: [m ²]	Area
l	Metre: [m]	Length
d	Metre: [m]	Diameter
r	Metre: [m]	Radius
m	Kilogram: [kg]	Mass
a	Metre per second: [m]	acceleration

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1. Chapter One: Introduction

1.1 Introduction and Context:

Water rocket launching can be an enjoyable activity and a great source of entertainment for children, which makes rockets ideal tools to convey knowledge about different physics concepts such as lift, drag, weight, and thrust generated through air pressurisation. Furthermore, the simplicity of the concept behind water rockets and their ease to manufacture made them very accessible.

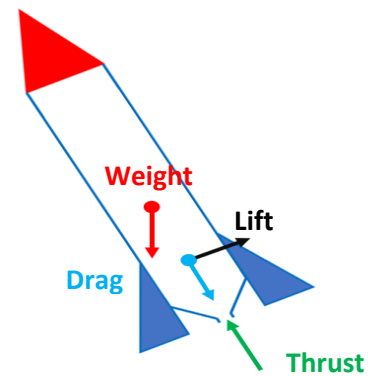


Figure 1.1-1: Forces acting upon a water rocket

What are they?

Water rockets are usually soda bottles to which cardboard fins, in most cases, are added. Additionally, a tennis ball is used as a rocket tip and a way to shift the centre of mass. The vessel uses water and pressurised air as fuel to project itself into the air.

How do they work?

1. The rockets are partially filled with water (about a 1/3 is considered optimal)
2. The air is then pressurised usually using a bike pump between 20 to 40 psi
3. Releasing the rocket causes the air to expand, pushing the water out the nozzle and creating thrust which ejects the rocket in the air to around 30m depending on the rocket design and its initial parameters.

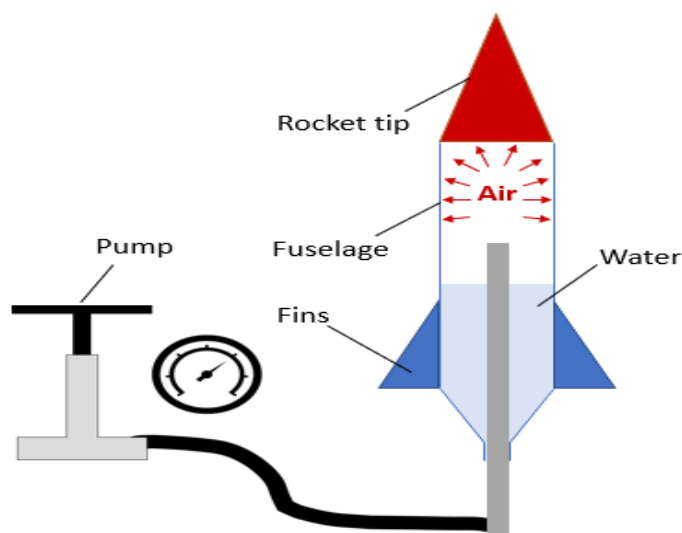


Figure 1.1-2: Water rocket launching process

Firing rockets can be a hazardous activity as the projectiles go rather high and can cause major injuries on their descent. Therefore, it is important to know where they would land and make sure they stick to their path. Conceiving stable rockets is done by shifting the centre

of gravity towards the tip. This report will bring focus on how rotation engendered by aerodynamic properties of a rocket is affecting its stability and overall performance.

Context behind rockets:

Public interest in water rockets is only growing bigger and bigger, it is encouraged through competitions such as: The NPL challenge that gathers 60 teams around 420 participants and an audience of several hundred spectators per year (Hennik research 2022, 2013), and throughout STEM activities done during primary, secondary, and higher education project (Hortman, 2017).

Both these actions are performed to attract the children's attention, increasing their interest in engineering, and quenching their thirst for knowledge. It also encourages creativity and thinking outside the box.

This growing interest in water rockets was exploited by different companies to make profit and that was done by selling:

- Ready kits that consist of a full water rocket kit such as TKC Stomp rocket that costs £13 at John Lewis® this kit includes a rocket, a rocket stand, and its launcher.
- Extension module kits that can be mounted on a standard soda drink bottle such as Darian's project (Nardi, 2019) and Rockit. Both rocket kits offer attachable rocket fins and a rocket tip.

Water rockets are a great way of recycling materials. Pollution is reduced by re-using and giving objects a second life.

After considering the context behind water rockets and their popularity, two options were available:

- Design a rocket kit that will be commercialised.
- Make this research accessible to others.

The personal motivations that were considered in making a decision were:

- The will to share the work done.
- Encourage kids to experiment and make rockets.
- Decrease pollution, reuse instead of recycling.

Consequently, it was chosen to make the report available instead of making a commercialised rocket kit. To achieve that, the project will be submitted to a forum where a water rocket forum.

Most of the materials used to make the rockets were recyclable and compostable. Therefore, making their disposal eco-friendly and unarmful to the environment.

1.2 Aim and objectives:

Project aim:

This project aims to study the effect of aerodynamically induced rotation on a water rocket's performance using accessible tools and appropriate engineering analysis methods.

Objectives:

Project objectives:

- Objective 1: Evaluate and research different accessible ways of assessing a rocket's performance.
- Objective 2: Design and fabricate water rockets utilising aerodynamics to induce or cease rotation.
- Objective 3: Assess the aerodynamics of water rockets using wind tunnel testing and CFD.
- Objective 4: Evaluate the performance of both water rockets using a video analysis tool.
- Objective 5: Identify the effect of rotation on water rockets and determine the limitations of the study and what potential improvements can be implemented.

Personal objectives:

- Improve CFD skills by simulating flow around a water rocket.
- Improve 3D modelling skills through 3D modelling of water rockets.
- Gain wind tunnel testing skills and acquiring a better understanding on repeatability of experiments and different calibrations needed to assure reliable results.
- Gain organisation skills using Gantt Chart and recognising different phases of the project.
- Acquire practical experience through running experiments and facing the onsite unexpected problems.
- Develop the ability to write a technical report and correctly use the resources available by identifying the key information needed from the documents and books used.

Performance and study definition:

This project aims to compare two rocket's performances for the same initial conditions:

Performance on rockets is usually defined by the max height reached, however in this study other parameters will be assessed such as the distance travelled on the X-axis, max velocity and the ability of the rockets to stick to their path.

The rockets were tested for the same initial conditions using both accessible tools and engineering analysis methods. The tools used for the study are as shown in Table 1.2-1:

	Tool	Use
Accessible Tool	Tracker Video Analysis	Record the path, Velocity and Height
Engineering Analysis Methods	Wind Tunnel Testing	Assess the aerodynamics of the water rockets
	CFD Simulations	Assess the aerodynamics of the water rockets and identify a key parameter to stability

Table 1.2-1:Project parameters definition

Initial testing conditions for the rockets consisted of:

- Same initial mass for both rockets
- Same initial pressure for both rockets
- Same initial air to water ratio
- Same cross-sectional area

In addition, for the purpose of making the study accessible to others and easy to reproduce, accessible tools were used in the production of the rockets.:

- Rocket parts were easy to acquire
- Both rocket fabrication costs were less than £21.93 which is the average price for water rocket kits

1.3 Project planning and resources:

Planning:

To tackle a project of such complexity, a Gantt chart was made. Gantt chart attached in Appendix 1 was made to follow the chronological development of the project, adapting the plan to the difficulties faced through updating the Gantt chart was crucial. The Gantt chart was found to be very useful in identifying milestones and key steps of the project. However,

it was found to be rather difficult to follow the initial plan due to the project being broad and undefined.

A dependency matrix was also made as shown in Appendix 2, the latter helped recognize what task relied on which and hence understand the priorities and urgency of achieving some tasks before others.

Before proposing the final objectives, initial objectives were defined. However, it was quickly observed that these objectives would not be met by the end of the project for the allocated time and due to new circumstances, they had to be changed and adapted as shown in Figure 1.3-1.

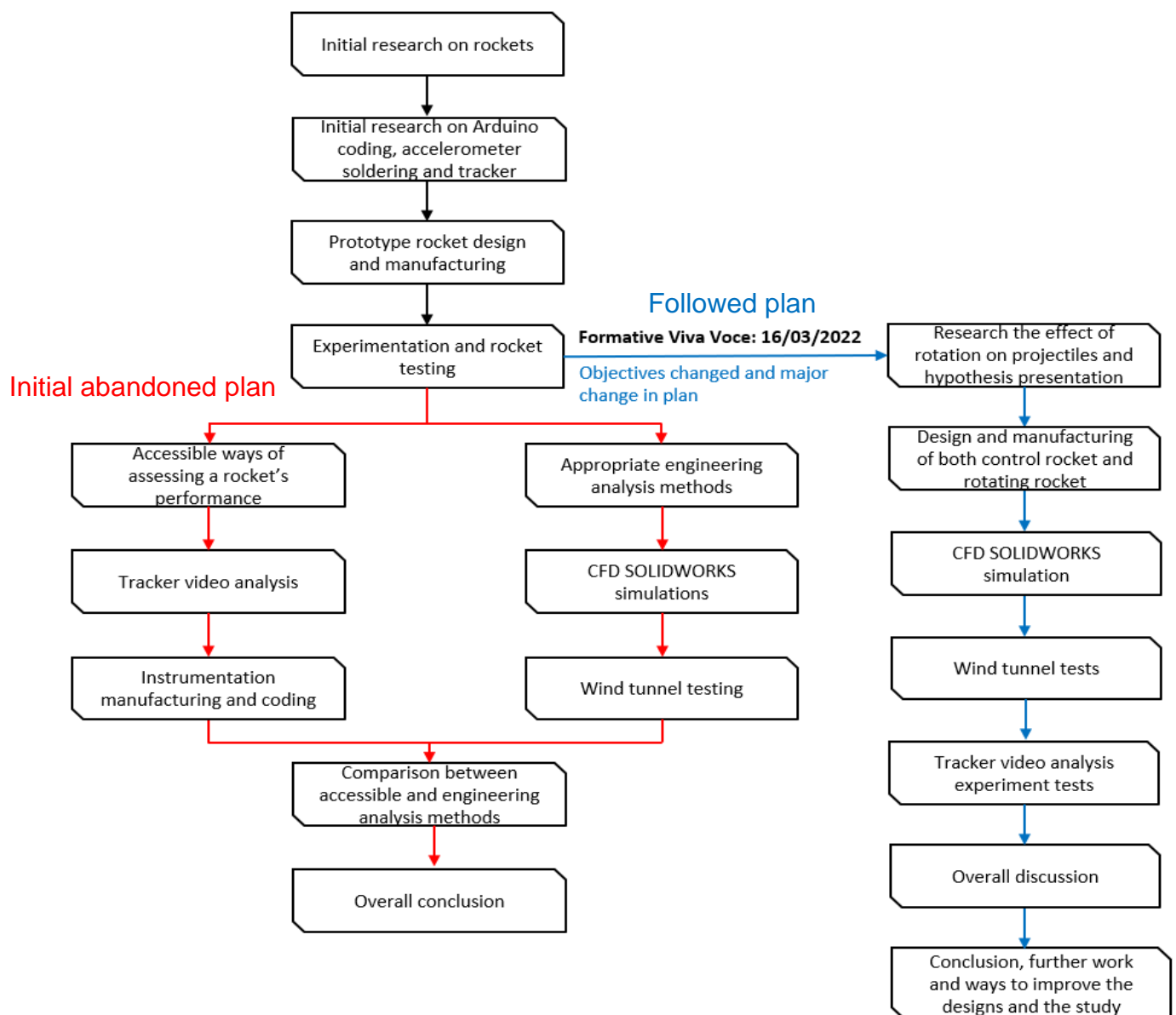


Figure 1.3-1: Project plan diagram

The tests done on the rockets designed following the initial plan were not completely disregarded. Quite the contrary, without these previous tests some key observations would

not have been possible, and they hence participated in making the next steps clearer and provide a better general outcome for the project.

Resources used:

Resources	Purpose
Human Resources	
Project supervisor	Providing guidance and advice on what steps to take to achieve good results on the project and provide feedback to improve the quality of the work done.
University lecturers and lab supervisors responsible	Provide guidance and training on how to use different tools provided by University of Brighton: Wind Tunnel, Laser Cutter, Soldering Labs, and 3D printing machines.
Hardware Equipment	
Sub-Sonic Wind Tunnel 2	Used to evaluate the drag coefficient of the rockets. In addition to measuring angular velocity.
Laser cutter	Cut the fins of the rocket
Printers	Poster printing
Software resources	
SOLIDWORKS® 2022	3D model of rockets. In addition to running CFD simulations on the designed rockets.
Microsoft Word	Dissertation write up
Microsoft Excel	Gantt chart and data organisation.
Microsoft Teams	Communication and organising weekly meetings with the supervisor.
Microsoft Publisher	Diagrams and poster
MATLAB R2021b	Used to plot the experiment results.
Tracker 6.0.6 Jan 2022	Provide video analysis on the performance of the rocket.
Other resources	
University of Brighton Libraries (Aldrich, Falmer, Queenwood, St Peter's House)	Access books. (Wind tunnel testing by Pope and British standards)
University of Brighton online resources Journals	Access journals and previous studies on water rockets.

Table 1.3-1: Table of resource used

Risk assessment:

After pinpointing the resources available making a risk assessment was key to avoiding unexpected last-minute difficulties. The risk assessment, Appendix 3, contained different ways to tackle or reduce the impact of potential obstacles that can be faced during the project.

The ethical implication of the project was added in Appendix 4.

1.4 Background research:

a. Rocket design and fabrication:

The National Physical Laboratory guide to building water rockets booklet was reviewed. The booklet provided useful instructions on how to make water rockets and what materials are usually used. The latter consisted of light waterproof materials for the fins to avoid water damage, PET plastic bottles because they withstand higher pressures. (De Podesta, 2006)

b. Tools used to assess a rocket's performance:

Various methods are used to assess a rocket's performance. Instrumentation is one of them, the Smart Water Rockets project covers the use of a pressure sensor and an accelerometer in a learning space camp program. This was used to record the max height reached by the water rockets and their acceleration (Gabriel, Kyle, Connor, Mathew, & Turner, 2015). Wind tunnel testing is a great way of assessing the aerodynamic properties for various objects making it a great tool for estimating the water rocket's drag coefficients it was used in previous research such as Analysis of a water-propelled rocket (Chris, 2005). Video analysis is another way of studying the rocket's performance and this tool is covered in deeper analysis in Chapter six: Video Analysis of Water Rocket Performance.

c. Stability of a water rockets:

The NPL guide delivered key information on the importance of making the rockets tip heavy to improve stability through shifting the centre of gravity.

Another paper published by the International Journal of Research and Analytical Reviews about analytical calculation on rocket stability was viewed. The article brought light into the Static Margin (SM) which indicates the rocket proneness to self-correct its direction towards its tip. Static margin is calculated by dividing the distance between the centre of gravity and the centre of pressure by the diameter, the rocket is considered stable for values of SM varying between 1 and 2 (Solomon & Areham, 2020).

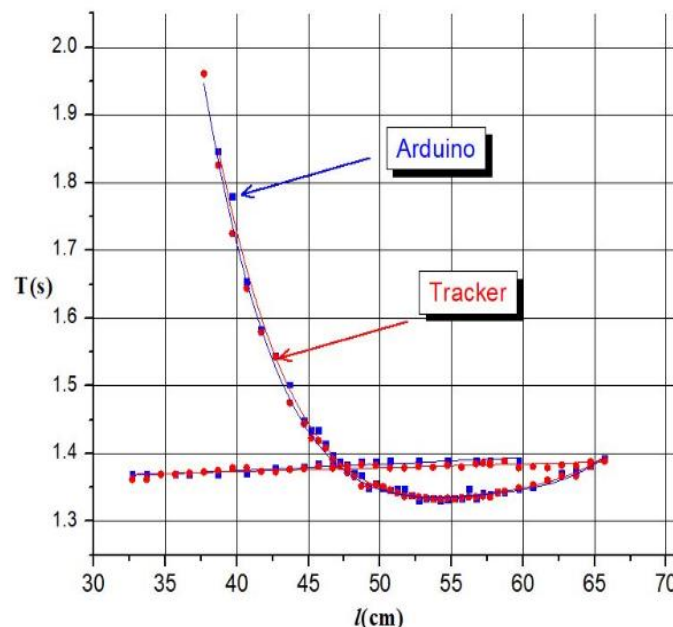
d. Video analysis:

Video analysis is a very common way to assess a rocket's performance. Quicktime™ a video player was used by the NPL as shown in Figure 1.4-1 **Error! Reference source not found..** The size of the rocket was taken as a reference length to evaluate the speed and acceleration of the rockets at launch. The rocket's max height is then calculated using SUVAT equations (De Podesta, 2006).



Figure 1.4-1: Video analysis of a water rocket at launch (De Podesta, 2006)

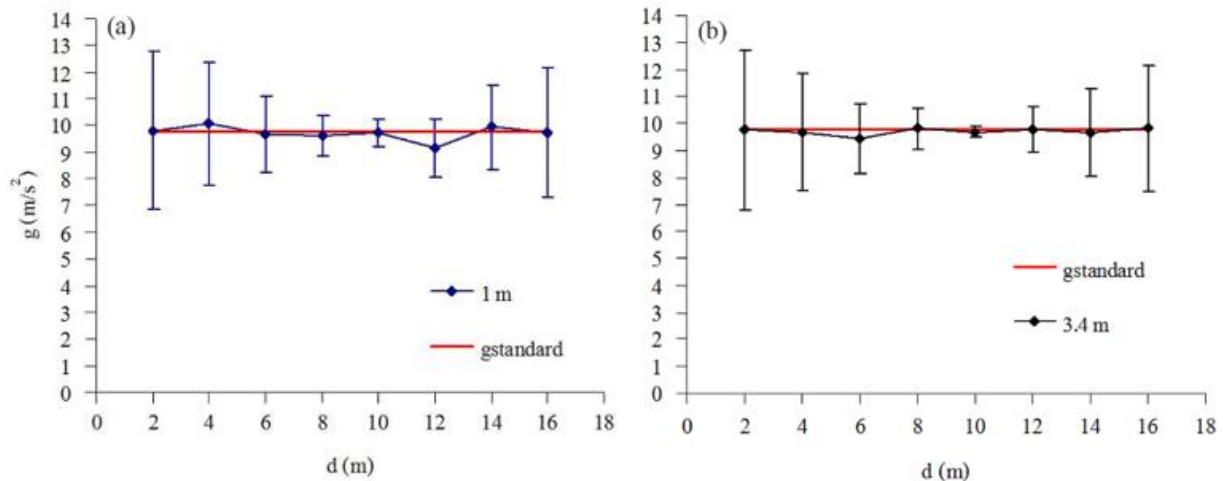
A study conducted by the University of Bucharest, Faculty of Physics on Didactic tools for study of the Kater's pendulum physical experiment was perused. The study compared the ability of tracker Software and Arduino to measure the oscillation of the Kater pendulum. The study allowed to evaluate the accuracy of tracker, Graph 1.4-1 bellow showed that both analysis methods' results were extremely close to each other and to the actual value (Cristina, B, Fabiola Sanda, C, & V, 2020).



Graph 1.4-1: Evaluation of the data obtained using an Arduino and tracker (Cristina, B, Fabiola Sanda, C, & V, 2020)

However, tracker's accuracy was critically affected by the distance from the studied object. Indeed, a different study done by Walailak University, Nakhon Si Thammarat, Thailand unveiled the effect of distance on accuracy in video analysis through measuring

the acceleration of a free-falling object for different camera distances, 2 to 16m with 2m intervals, (Sirisathitkul, Glawtanong, Eadkong, & Sirisathitkul, 2013) the results of the research were displayed in Graph 1.4-2 below:



Graph 1.4-2: Variation in gravity for different camera distances (a) ball falling from 1m (b) ball falling from 3.4m (Sirisathitkul, Glawtanong, Eadkong, & Sirisathitkul, 2013)

1.5 Hypothesis:

From the background research done so far, the effect of rotation on the rocket would be to increase its stability and improve its displacement. Nevertheless, the rotation of the rocket is also expected to encourage the rocket to drift slightly to the right or to the left depending on whether it is rotating clockwise or anticlockwise.

2. Chapter Two: Design and Fabrication of Water Rockets

2.1 Design and manufacturing of initial prototypes:

Prototype rockets were tested first to have an approximation of how water rockets work and the key factors that affect their performance. These initial rockets were designed as follows:

Materials used:

	Part	Description	Provider and cost
Prototype 1	Rocket tip	Compostable plant pots 4 were used to make the tip of the rocket heavier and improve stability	B&Q® £1.75
	Rocket fuselage	A 1.25l Coca-Cola® bottle	TESCO® £0.99
	fins	3 triangular cardboard fins	-
Prototype 2	Rocket tip	Noodle pot Compostable pot	ASDA® and B&Q® £1
	Rocket fuselage	A 1.75l Coca-Cola® bottle	TESCO® £1.97
	fins	3 Triangular cardboard fins	Wellpackeurop e.com £3.99
Other	-	Duct tape	B&Q® £3.42
	-	Super glue	B&Q® £6.6
Total Cost	-		£19.72



Figure 2.1-1: Prototype 1 in wind tunnel

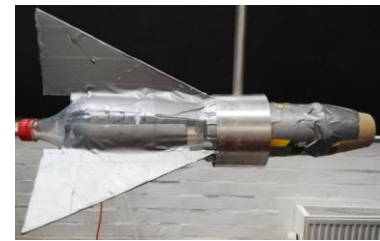


Figure 2.1-2: Prototype 2 in wind tunnel

Table 2.1-1: Bill of materials for the prototypes

The rockets were put together using glue and duct tape. And the fins were spaced equally.

2.2 Rocket design specifications and requirements:

General specification on both rockets:

1. Have a fuselage more than 0.5m to increase the height of its centre of pressure.
2. Weigh less than 0.5kg.
3. Be fabricated from easily procurable materials.
4. Cost less than £21.93 to produce each as covered in Appendix 5: Rocket kits pricing.

5. Have a drag coefficient that does not exceed 0.9.
6. Be able to withstand high pressures, 50psi.
7. Be strong enough to withstand impact against the ground.
8. Not take damage when in contact with water.

Design requirements specific to the rotating rocket Vortex:

- a. Rotate through contact with air flow minimum velocity of 4m/s.
- b. Weigh as much as the control rocket 'Ctrl'.
- c. Have cross-sectional area equal to Ctrl.

Design requirements specific to Ctrl:

- a. Not rotate when in contact with air flow.
- b. Weigh as much as Vortex.
- c. Have the same cross-sectional area as Vortex.

2.3 Initial Vortex designs:

Vortex, the rotating rocket had two initial designs:

1st design: twisted fin design that consisted of:

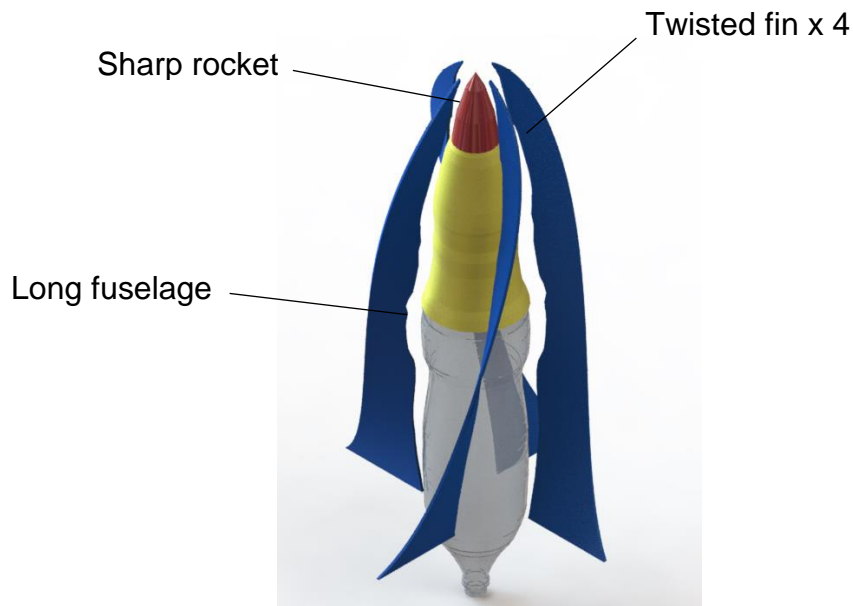


Figure 2.3-1: Exploded view of twisted fin rocket CAD model

The twisted fins would allow the rocket to spin as it flies up in the air.

Limitations:

Manufacturing of twisted fins limitations:

- 3D printing is time-consuming due to the waiting list plus the fins would be fragile and break easily.
- Twisting materials would produce a shape less precise than modelled in CAD software.
- Air acting against the fins could cause them to deform if twisted using weak materials resulting in faulty data.

2nd design bent fin rocket:

After considering the design limitations of Vortex it was decided to produce a new design, Figure 2.3-2 displayed below, was easier to manufacture and less time-consuming.

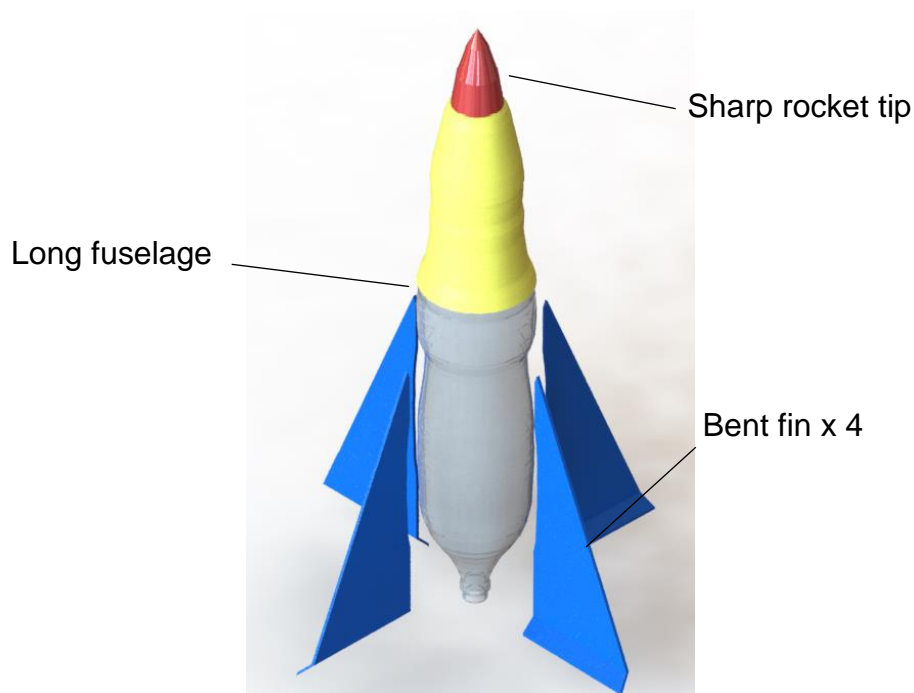


Figure 2.3-2: exploded view of bent fins rocket CAD model

2.4 Final designs and fabrication:

Two rockets were used in this study. A control rocket 'Ctrl' was designed to be used as a reference point to assess the rotating rocket's performance 'Vortex'. Both rockets were designed to have the same mass and same cross-sectional area.

a. Rocket tip:

The study on rocket tips issued by Peak of Flight Newsletter was very helpful in determining what shape of nose cone to use. The Figure 2.4-1 shows that long elliptical cone shape is the best shape for reducing drag, this design was chosen for both rockets. (Van Milligan, 2013)

a. Fuselage:

Both rockets were designed to have a long fuselage to increase the height of their centre of gravity.

b. Fins:

Both rockets were designed to have 4 fins all placed at equal distances from each other at 90°.

The fins were triangular to ease their manufacturing process. The bottom of the fins contained an extrusion at 45° that allowed Vortex to spin. For Ctrl, the fins were designed to counter each other rotation by extruding 2/4 fins on the other side.

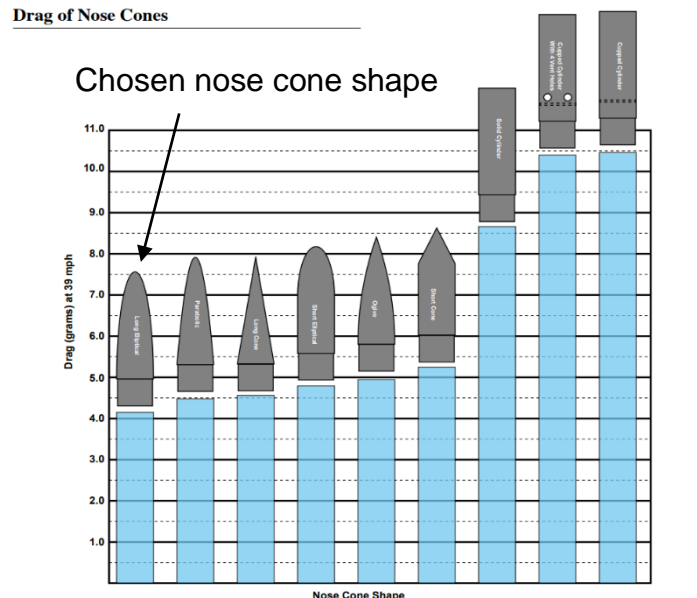


Figure 2.4-1: Adapted from: Drag of different nose cone shapes (Van Milligan, 2013)



Figure 2.4-3: Top view of Ctrl displaying the disposition of the fins

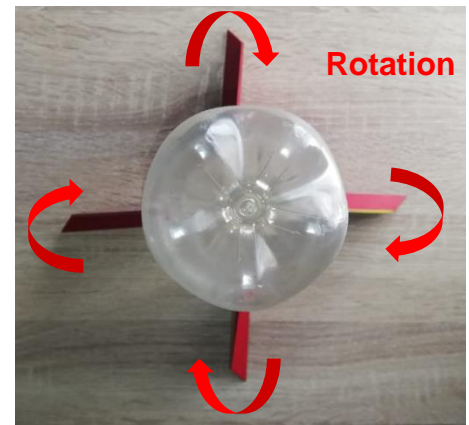


Figure 2.4-2: Top view of Vortex displaying the disposition of the fins

Materials and cost:

List of materials used with justification:

Rocket part	Material used	Justification
Fuselage	1.75l Coca-Cola® bottle	PET plastic can withstand high pressures. Coca Cola is the most popular soft drink in the world hence easy to acquire.
	Pot noodle	Increase the length of the fuselage to make the rocket more stable Accessible and easy to get a hand on.
Rocket tip	Compostable pots	Allows making the desired rocket tip shape. Eco friendly and easy to dispose of.
	Deodorant stick lid	Allows making the parabolic desired shape. Cheap and accessible.
Fins	2mm MDF wood	Rigid material that will not deform under the forces it will be subject to. Easy to dispose of biodegradable material.

Table 2.4-1: table of materials used and justification

Bill of materials used:

Rocket part	Material used	Qty	Cost per unit	Machining cost	Total cost	Provider
Fuselage	1.75l Coca-Cola® bottle	2	£1.97	-	£3.94	TESCO®
	Pot noodle	2	£1	-	£2.00	ASDA®
Tip	Compostable pots	1	£1.75	-	£1.75	B&Q®
	Deodorant stick lid	2	£1	-	£2	WAITROSE®
Fins	3mm MDF wood sheet	1	£2.16	£4 (£60/h)	£6.16	Cutmyplastic.co.uk
Other	Duct tape	1	£3.42	-	£3.42	B&Q®
	Super glue 15g	1	£6.60	-	£6.60	B&Q®
Total cost	-				£25.87	-

Table 2.4-2: Bill of material for the rockets

The costs can be brought down by acquiring certain components differently, as these are priced for their contents while the receptacle is the important part for the rockets. One way they can be acquired is through recycling centres where plastic coke bottles can be acquired for free. In addition, some of the components needed are used daily such as the deodorant stick, pot noodles and even coke bottles. Further reduction in cost can be achieved by using cheaper manufacturing methods such as hand saws to cut the MDF, saws are also more accessible than laser cutters.

Fabrication of the rockets and their different components:

The rockets:

The rockets were put together using super glues and tape. Some lines were drawn on the plastic bottle beforehand to make sure the fins were equally spaced.

The rotating fins:

A triangle and a trapezoid shape were laser cut from a 2mm MDF sheet as shown in Figure 2.4-4

To achieve the 45° angle specified in the CAD model, a wooden piece with a 45° cut was used as a base. The fins were then held in place using tape and then super glued to keep the desired shape as shown in Figure 2.4-5 below:



Figure 2.4-5: Fin on wooden base Side view



Figure 2.4-4: Fin cut

Fabrication outcome:

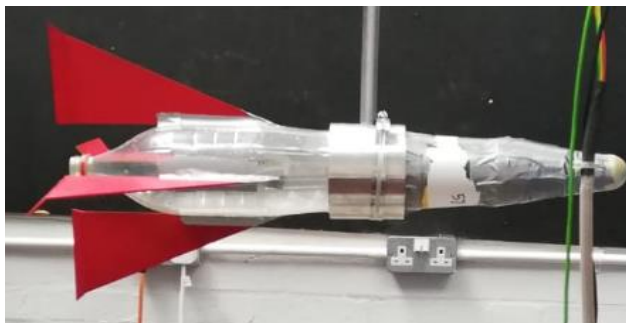


Figure 2.4-7: Vortex in wind tunnel

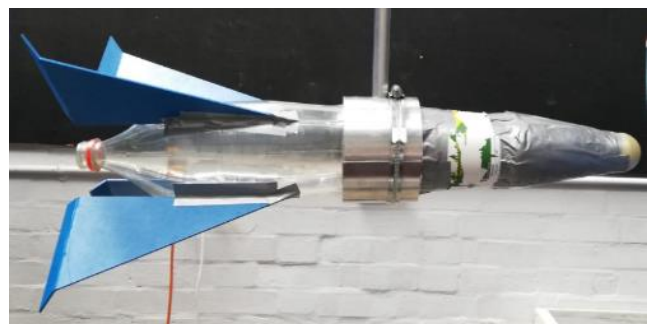


Figure 2.4-6: Ctrl in wind tunnel

2.5 Mass distribution and rocket stability

The principle behind stability in water rocket:

The stability of the rockets mainly depends on the position of the centre of gravity regarding the centre of pressure (Solomon & Areham, 2020).

$$SM = \frac{h_{CG} - h_{CP}}{d} \dots\dots\dots(2.5-1)$$

where: $1 < SM < 2$ (Nanditta, et al., 2021)

SM being the Stability Margin as shown in Figure 2.5-1

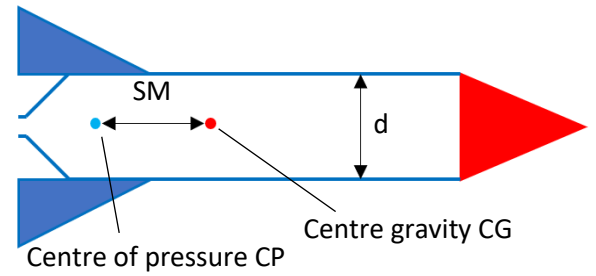


Figure 2.5-1: Diagram displaying the CP and CG disposition on a stable rocket

Calculation of the ideal position of the centre of gravity and the mass of the rocket tip:

Assumptions made for the calculations:

- The centre of gravity and centre of pressure were assumed to be positioned along the centre axis of the rocket.
- The mass is assumed to be distributed evenly for a set material or rocket part.

Centre of pressure:

The position of the centre of pressure was measured using SOLIDWORKS® flow simulations. (The simulation done was explained in detail in the next chapter) $h_{CP} = 17cm$

Centre of gravity:

The rockets were set to have the same mass for the study. Different parts of the rockets were weighted, and their mass were recorded in Table 2.5-1.

Mass	[g]	[kg]
m_{Fins}	96	0.096
m_{Bottle}	38	0.038
$m_{Initial}$	134	0.134
m_{Tip}	?	?

Table 2.5-1: Rocket part's masses

- Centre of gravity of the fins:

Centre of gravity of a triangle is given as:

$$h_{CGfins} = \frac{h_{fin}}{3} = \frac{21.344}{3} = 7.1cm = 0.071m$$

Centre of gravity of a coke bottle was found to be:

$$h_{CGbottle} = 19.19cm = 0.1919m$$

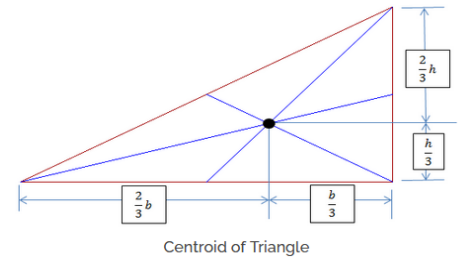


Figure 2.5-2: Triangle centroid (Afsar, 2013)

- Initial centre of gravity: fins+ bottle

$$m_{Initial} \times h_{CGInitial} = h_{CGfins} \times m_{fins} + h_{CGbottle} \times m_{bottle} \dots\dots\dots(2.5-2)$$

Rearranging (2.5-2) for $h_{CGInitial}$:

$$h_{CGInitial} = \frac{h_{CGfins} \times m_{fins} + h_{CGbottle} \times m_{bottle}}{m_{Initial}} = \frac{0.071 \times 0.096 + 0.1919 \times 0.048}{0.144} = 0.1114m = 11.14cm$$

- Ideal centre of gravity height:

Rearranging (2.5-1) for h_{CG} :

$$h_{CG} = SM \times d + h_{CP}$$

d: diameter of the fuselage

$$d = 10.3cm \text{ and } h_{CP} = 17cm$$

For: $SM = 1.2$

$$h_{CG} = 1.2 \times 0.103 + 0.17 = 0.2936m = 29.36cm$$

The height of the CG for the rocket tip was measured using SOLIDWORKS®:

$$h_{CGTip} = 41.16 cm = 0.4116m$$

$$m_{Initial} \times h_{CGInitial} + h_{CGTip} \times m_{Tip} = h_{CG} \times m_{rocket} \dots\dots\dots(2.5-3)$$

$$\text{And: } m_{rocket} = m_{Tip} + m_{Initial} \dots\dots\dots(2.5-4)$$

By substituting (2.5-4) in (2.5-3):

$$m_{Initial} \times h_{CGInitial} + h_{CGTip} \times m_{Tip} = h_{CG} \times (m_{Tip} + m_{Initial}) \dots\dots\dots(2.5-5)$$

Rearranging (2.5-5) for m_{Tip} :

$$m_{Tip} = \frac{(h_{CG} - h_{CGInitial}) \times m_{Initial}}{h_{CGTip} - h_{CG}} = \frac{(29.36 - 11.14) \times 134}{41.16 - 29.36} = 214g = 0.214kg$$

Total calculated rocket mass: $m_{rocket} = m_{Tip} + m_{Initial} = 214 + 134 = 348g = 0.348kg$

Actual mass measured using a scale:

$$m_{rocket} = 374g = 0.374kg$$

3. Chapter Three: CFD of Water Rockets

With the objective of accurately identifying the position of the water rocket's CP, SOLIDWORKS® flow simulations were run. In addition, airflow was simulated on Prototype2 to have a preliminary estimation of CD plus compare the results with wind tunnel testing.

3.1 Meshing:

A mesh independent study was conducted to determine the mesh that would provide accurate results within acceptable computational time.

Mesh characteristics set:

- Variation in Fz and Tx of 3% for an increase of 30,000 cells.
- Computational time less than 5min.

The study consisted of choosing an initial number of cells with a defined refinement level. Then, running a flow simulation, collecting the data (Drag force and Torque) and comparing the results with each mesh tested.

Mesh	Domain cells	Local mesh cells	Total cells	Computational time [min]	Tx	Fz
Mesh1	20515	-	20515	0.25	2.68	12.63
Mesh 2	63555	-	63555	1	2.4	12.88
Change 1-2	43040	-	43040	0.75	-10%	2%
Mesh 2	63555	-	63555	1	2.4	12.88
Mesh 3	131576	-	131576	2.75	2.48	13.76
Change 2-3	68021	-	68021	1.75	3%	7%
Mesh 3	131576	-	131576	2.75	2.48	13.76
Mesh 4	142851	22806	165657	3.8	2.39	14.07
Change 3-4	11275	22806	34081	1.05	-4%	2%
Mesh 4	142851	22806	165657	3.8	2.39	14.07
Mesh 5	419357	167823	587180	29	2.45	14.3
Change 4-5	276506	145017	421523	25.2	3%	2%

Table 3.1-1: Table of the Mesh considerations and their variations

The change between Mesh 1 and 2: Mesh 2 had 43040 cells more the initial mesh the variation in Fz was within the tolerance set, however the variation in Tx did not fall within the tolerance set. 10% for Tx and 2% for Fz

For a variation of 43,040 cells → 10% and 2%

The change 2-3: Mesh2 had 68,021 cells less than Mesh 3. This time the variation in Tx fell within the set tolerance with only 3% change. The Fz change on the other hand did not fall within the acceptable variation set reaching a variation of 7%.

For a variation of 68,021 cells → 3% and 7%

The change 3-4: Mesh 4 contained overall 34,081 cells more than Mesh3. Mesh 4 also introduced local mesh with 22,804 cells this mesh was done on the rocket tip and the fins. 4% for Tx and 2% for Fz

For a variation of 34,081 cells → 4% and 2%

The change 4-5: Mesh 5 surpassed Mesh 4 by 421,523 total cells. The values of Fz and Tx were 2% and 3% respectively. Mesh 5 took about 7 times the computational time necessary for Mesh 4.

The percent of variation in the results obtained between Mesh 1-2, 2-3 and 3-4 did not fall within the initial specification as they were above 3%. The variation 4-5 fell within the specified 3%. Choosing between Mesh 4 and Mesh 5: The computational time for Mesh 5 was way over the set value of 5 min, eliminating Mesh 5 as an option. Consequently Mesh 4 was chosen having provided the best results within acceptable computation time and complying with the initial specifications set.

3.2 Simulation Setup:

For all simulations:

The simulation was set to external flow simulation and the fluid used was set to pre-defined air.

Initial drag simulations on Prototype2:

Simulations on Prototype2 were run as an attempt to reproduce the wind tunnel test results. This allowed the assessment of how close the simulations were to reality. Same initial conditions as wind tunnel tests were used: $P_{amb} = 101323.2\text{Pa}$, $T_{amb} = 293.15^\circ\text{K}$ as shown in Figure 3.2-1

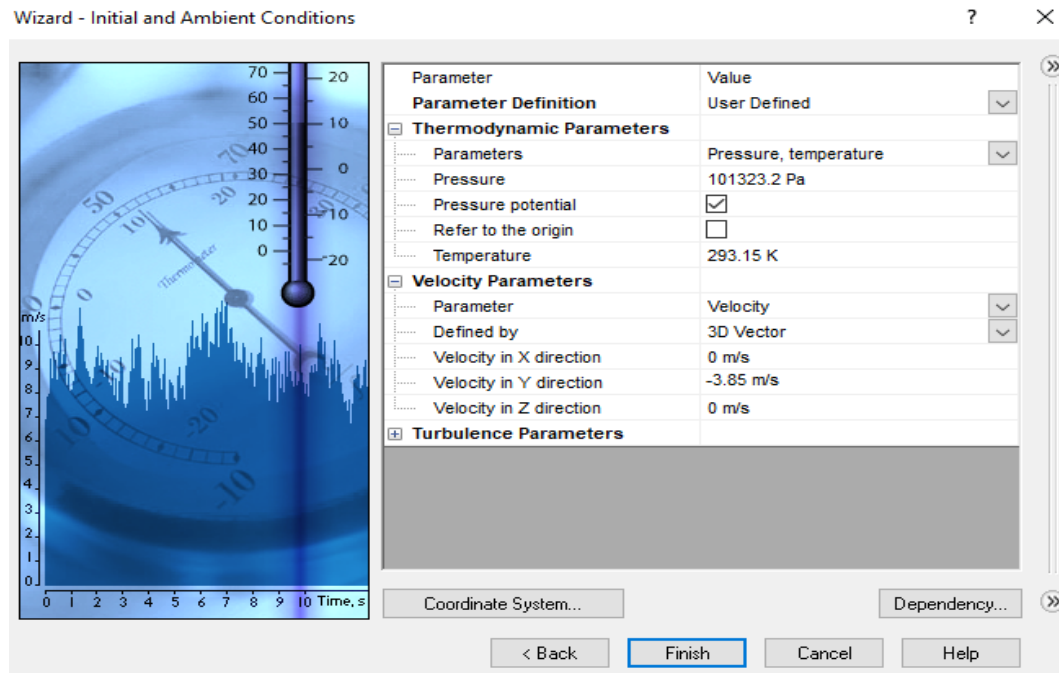


Figure 3.2-1: SOLIDWORKS flow simulation initial conditions

The air flow simulations were then run using the same air velocities observed during the experiment: (3.85m/s, 6.55m/s, 9.35m/s, 12.25m/s, 15.1m/s, 18m/s and 20.95m/s).

The air was simulated to be facing the rocket tip on the Y axis. The goals of the simulations were set to F_y (Force on the Y axis)

Note:

As the humidity in the wind tunnel testing room was not known, it was not taken into account during the simulation.

Centre of pressure location:

Simulations on Vortex were run to identify the position of its centre of pressure.

Initial simulation conditions were set to default and air velocity was set to 20m/s on the Z axis.

The goals of the simulations were set to F_z (Force on the Z axis) and T_x (Torque on the X axis)

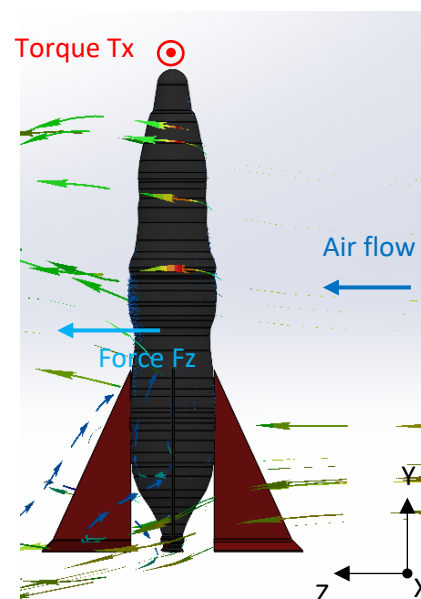


Figure 3.2-2: Flow simulation to identify the position of CP

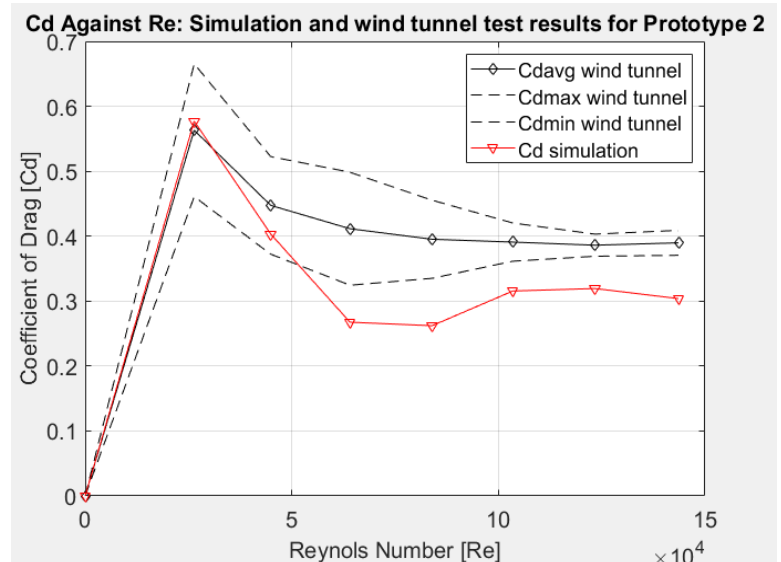
3.3 Data and results:

Initial results from 'Prototype2':

To evaluate the accuracy of the SOLIDWORKS® flow simulation, the observed drag coefficients from the simulation were plotted with the wind tunnel test result.

Graph 3.3-1 shows the collected results:

The max and minimum drag coefficients were plotted to display the variation in wind tunnel testing and compare it with the simulation data. The mean values for Cd from the wind tunnel were used to allow an overall comparison.



Graph 3.3-1: Cd against Re for Wind tunnel test and simulation

(The conditions of the wind tunnel test and method are covered in detail in Chapter Five)

Centre of pressure:

The results of the simulation run are as shown in Table 3.3-1 :

Where Fz is the force on the Z axis and Tx is the Torque on the X axis.

Fz [N]	Tx [Nm]	CP [m]
14.072	2.39	0.169841

Table 3.3-1: Fz Tx and CP results from simulation

And CP is calculated by:

$$CP = \frac{T_x}{F_z} = 0.169841m \approx 17cm$$

3.4 Discussion and analysis:

Initial tests on prototype2:

The results showed a difference ranging from 23% to 4% between the actual test and the simulation.

Graph 3.3-1 shows, the simulations were close to the actual wind tunnel tests even though the values were not identical, they still followed similar trends.

Reasons for the difference in the results:

- Surface friction is minimised (smoother CAD model).

- The effect of humidity was not considered.
- The meshing: the number of cells generated is limited by the computation time necessary to accomplish the simulations.

Centre of pressure:

Considering the observations made after the prototype tests, additional CP positions were calculated and displayed in Table 3.4-1 :

	Fz [N]	Tx [Nm]	CP [m]
Fz	14.07	2.39	0.17
Fz+23% Fz	17.31	2.39	0.138
Fz+ 4% Fz	14.63	2.39	0.16

Table 3.4-1: CP variation

New calculated CP values were lower than the simulation value. However, to make sure the rocket will be stable and allow a margin of error the worst value of CP was used for further calculations. (CP=17cm)

The position of CP was rather low compared to the size of the rocket, 30%, of length of the rocket, the fins position helped bringing the centre of pressure down and hence decrease the mass needed on the tip to allow the rocket to be stable.

4. Chapter Four: Development of a Wind Tunnel Test Rig

In order to test Vortex in the wind tunnel and measure its angular velocity, a special wind tunnel test rig was needed.

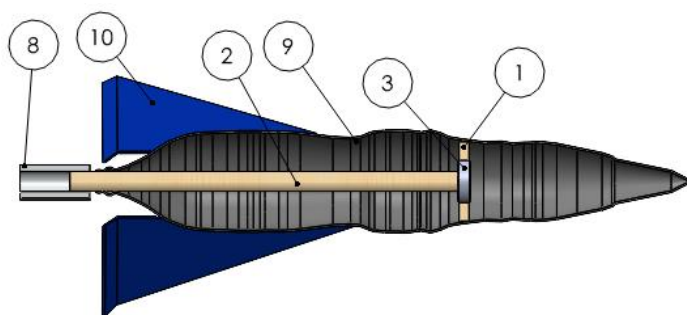
4.1 Design requirements:

The specifications of the wind tunnel test rig were:

- Allow the rocket to rotate.
- Fit inside the rocket nozzle diameter of 21.5mm.
- Allow to be linked to the load cell, contain a hole, 8mm in diameter.
- Hold the rocket in place facing toward the wind tunnel.

4.2 Initial design:

A wooden axle that linked the base inside the fuselage to the aluminium load cell link, the base was designed to be a circular wooden piece with a hole in its centre that fits the bearing_623-2rs1_2.



- 1: Wooden base
- 2: Wooden axle
- 3: Bearing_623-2rs1_2
- 8: Aluminium link to load cell
- 9: Rocket fuselage
- 10: Rocket fins

Figure 4.2-1: Initial design for wind tunnel test rig

Design limitations:

- High friction generated by the bearing.
- Difficulty in aligning the axle, the bearing and the wood base to keep a 90° angle.

4.3 Final design:

The final design consisted of a coke bottle to which a hole was drilled on its base. Then the top of another rocket was cut and fixed to the bottom of the first bottle. A wooden axle is then slid through both



Figure 4.2-1: Fuselage for the wind tunnel test rig

bottle openings and through the aluminium link.

The new design appeared to be causing less friction and was cheaper.



Figure 4.3-2: Aluminium link and wooden axle for the test rig

4.4 Materials and costs:

Part	Qty	Cost per unit	Machining cost if applicable	Total cost	Provider
Wooden axle	1	£2	-	£2.00	Wood piece provider
1.75l Coca-Cola® bottle	1	£1.97	-	£1.97	TESCO®
2l Diet Lemonade	1	£0.2	-	£0.2	ALDI®
Aluminium link to load cell	1	£7.38	£16.25	£23.63	Parallelprecision.co.uk Aluminium-online.co.uk
Total cost		-		£27.8	-

Table 4.4-1: Wind tunnel test rig bill of materials

4.5 Fabrication:

A Dremel (Model 4000 corded RS: 707-3487) was used to cut a hole at the bottom of the 1.75l Coca-Cola® bottle, the hole was made bigger than the wood axle that goes through it by 2mm to allow rotation with no friction or interference. The tip of another bottle was cut using a reciprocating saw. The two bottle parts were glued together using a PVC pipe (21.5mm in diameter) to ensure the alignment of both bottle openings.

The rest of the rocket fuselage (noodle pot, compostable plant pot and the tip) were then glued and so were the fins.

The aluminium link to the load cell was machined using a 3axis milling machine (XYZ3500 milling machine). A hole of 20mm was drilled in its centre to allow a tight fit with the 20mm wooden axle and prevent any rotation from occurring. To fix the aluminium link to the rod that connects to the load cell, a smaller hole of 8mm in diameter was drilled on the top side of the aluminium block. The sharp edges of the block were smoothed to avoid cuts.

Appendix 4: Engineering drawings Load cell link

5. Chapter Five: Wind Tunnel Testing of Water Rockets

With the aim of evaluating the drag generated by the designed rockets and estimated the angular velocity reached by Vortex, a series of wind tunnel tests was conducted.

Wind tunnel testing was chosen as a tool to study aerodynamics of rockets for several reasons. First, it allows repeatable testing increasing the precision of the results obtained. Furthermore, it can provide differing air flow velocities which allows different testing scenarios. Finally, the results obtained are really close to reality, because wind tunnel testing takes into account real life parameters such as, the humidity and small imperfections that the objects have.

5.1 Materials Used:

Table 5.1-1 provides a list of the materials used during the wind tunnel tests.

Tool	Purpose	Model and reference	Range and accuracy
Vane Anemometer	Measuring the air speed	Testo 416 Telescopic Vane (RS 512-0301)	0.6m/s - 40m/s $\pm 0.2\text{m/s} + 1.5\%\text{mv}$
Load Cell	Measure the force acting on the rocket	Tedea Huntleigh Wire Lead (RS 443 8128)	$\pm 3\Omega$
Digital multimeter	Convert the voltage reading from the load cell to Force in [N]	Black Star 4503 Intelligent Multimeter 421/423	-
9V Power supply	Power the load cell with 9V	Topward electric instruments, MODEL: TPS-2000	-
Mercury barometer and thermometer	Measure ambient pressure and temperature	Griffin and George LIMITED	0-815 mmHg 0 - 50 °C
Hose clamp and rocket fixture	Hold the rockets in place during the tests	-	-
Vortex's mount	Used to allow the rotation for the rotating rocket and hence evaluate its angular velocity	-	-
Photo/ contact tachometer	Measure the angular velocity of Vortex	RS PRO tachometer (123-8779)	$\pm 0.05\%$

Table 5.1-1: List of materials and tools used for wind tunnel testing

5.2 Methodology:

Initial experiment parameters:

Before any testing was done the initial pressure and temperature were recorded using a mercury barometer and a thermometer.

Set-up:

- Load cell was held in place using the balance above the open testing area that was provided with the wind tunnel.
- The mount that the rockets were fixed to was linked to the load cell to measure the force generated by the air.
- The vane anemometer was placed on the side of the wind tunnel to not disturb the flow on the rockets. It was set at: length=19.2cm and height=19.4cm from the edge of the wind tunnel. (Wind tunnel section diameter is 1m) 0.273m away from the centre.
- Multimeter was linked to the load cell to convert the voltage output of the readings into force in [N].
- For measuring the angular velocity reflective tape was placed on the compostable pot part of the rocket as it does not reflect light and was used to measure the angular velocity using a tachometer.

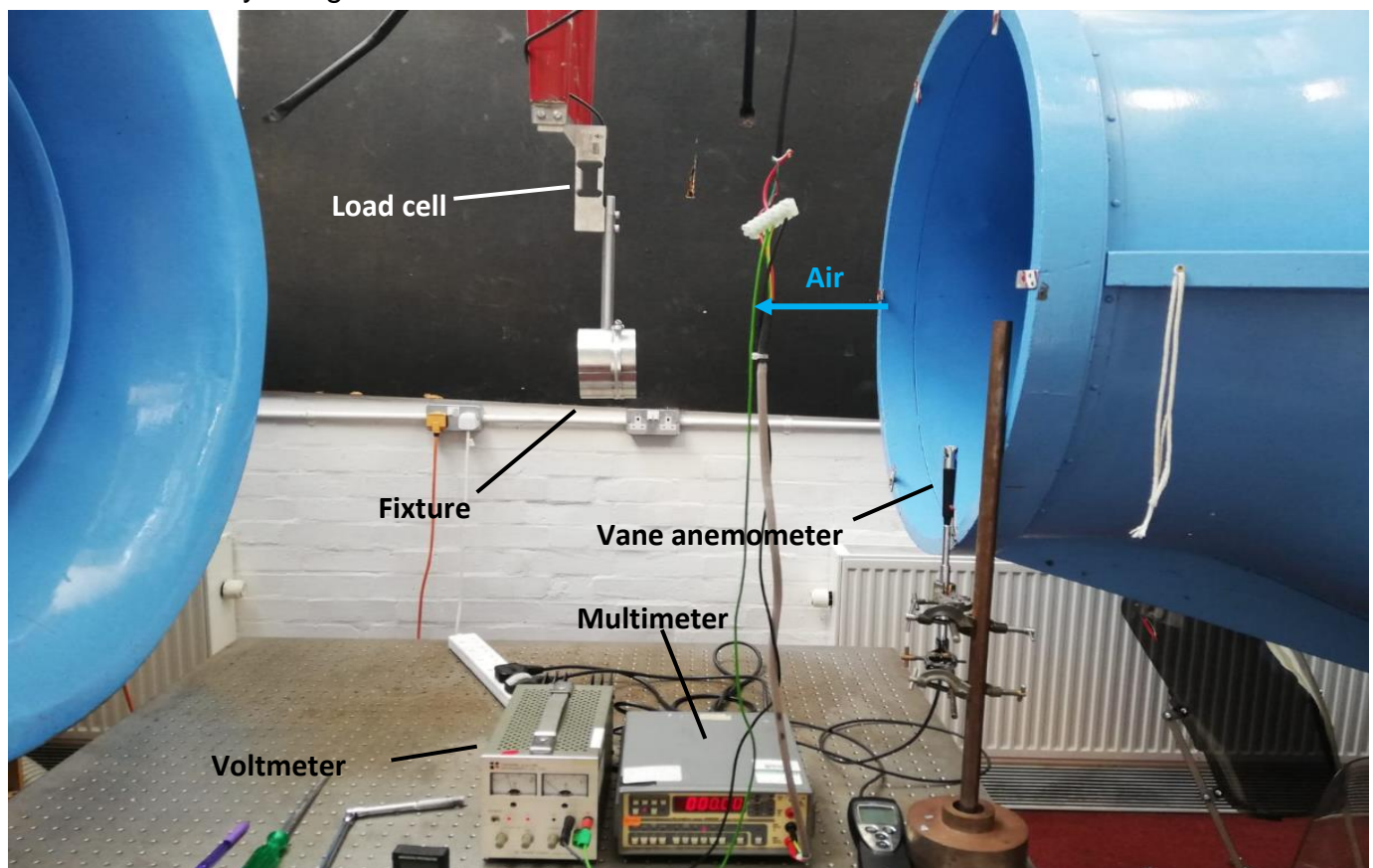


Figure 5.2-1: Wind tunnel experiment set-up

Calibration:

Mount calibration:

The velocity of the air and the drag force exerted on the mount on its own was measured before and after the experiments for each rocket.

Testing of each rocket:

All the rockets were mounted on the hose clamp mount for the drag force measuring test. While in the torque measuring test Vortex was mounted on the test rig that allowed rotation to measure the angular velocity using the tachometer.

The initial tests done on the prototypes were run from 200 up to 800 RPM at 100 intervals. Values of drag force and velocity were taken at each test point. After a thorough analysis of the results, it was decided to set the test points using the measured velocity on the test point. Hence, measuring the drag force for defined air velocities, where the anemometer is held at the same position.

Velocities drag force was measured at:

Test point 1: $V_f = 3.8\text{m/s}$, Test point 2: $V_f = 6.45\text{m/s}$, Test point 3: $V_f = 9.05\text{m/s}$, Test point 4: $V_f = 11.95\text{m/s}$ and Test point 5: $V_f = 14.75\text{m/s}$.

Ctrl and Vortex were tested 4 times to make sure the results were accurate.

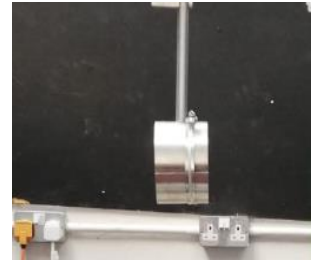


Figure 5.2-2: Calibration of rocket fixture



Figure 5.2-4: Prototype 1 in wind tunnel



Figure 5.2-3: Prototype 2 in wind tunnel

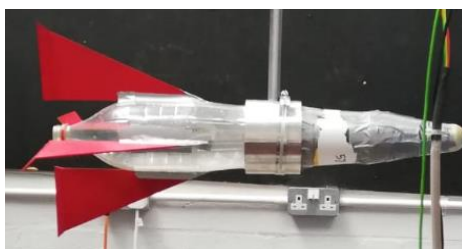


Figure 5.2-6: Vortex in wind tunnel

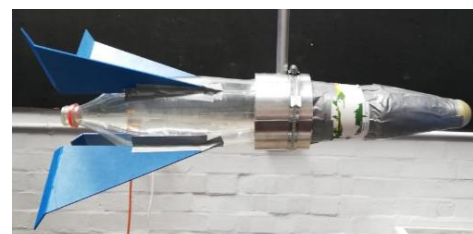


Figure 5.2-5: Ctrl in wind tunnel

Vortex was also tested on the special test rig to have an estimation of its angular velocity the rocket was fixed as shown in Figure 5.2-7.

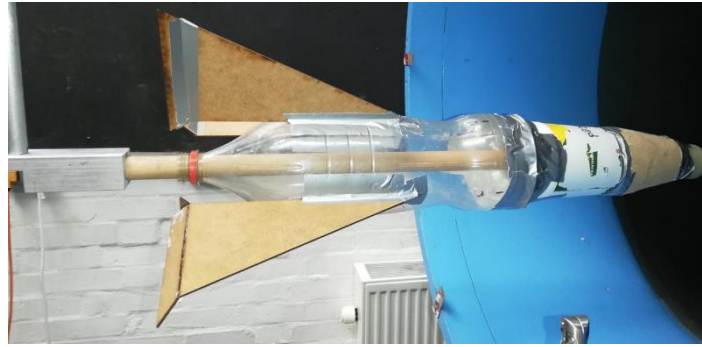


Figure 5.2-7: Vortex on the rotating test rig

A protection net was used during the test of Vortex due to the risk of injuries from flying sharp fins.

5.3 Data and Results:

Calculated results:

Before any calculation was done, the drag force measured during the calibration was subtracted from the final drag value displayed.

Formulae used:

Calculating the air density for each wind tunnel test conducted:

$$\rho = \frac{P_{amb}}{T_{amb} \times R}$$

Drag coefficient equation:

$$Cd = \frac{2Fd}{A_{cross-section} \times \rho \times Vf^2}$$

Reynolds number formula:

$$Re = \frac{\rho \times l \times Vf}{\mu}$$

The cross-sectional area:

The cross-sectional area was taken from the top view of each rocket as shown in Figure 5.3-1 and was measured by:

$$A_{cross-section} = A_{top fuselage} + A_{top fins}$$

A_{cross-section} is the silhouette of the rocket projected on the top view. The cross-sectional area and the characteristic of each rocket are shown in Table 5.3-1

Rocket	Cross-sectional area [m ²]	Characteristic length [m]
Prototype 1	0.0060	0.0838
Prototype 2	0.0090	0.1030
Ctrl	0.0144	0.1030
Vortex	0.0144	0.1030

Table 5.3-1: Dimensions of all the rockets tested

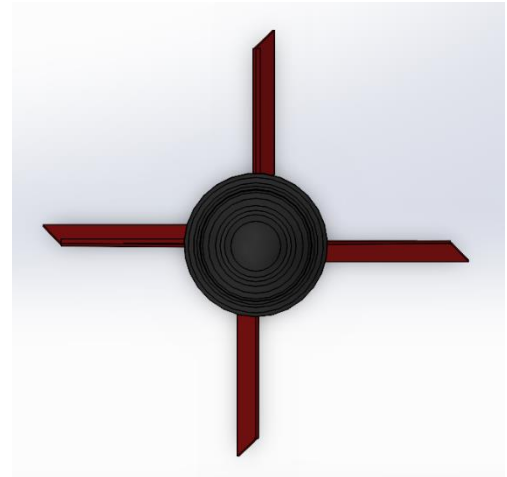
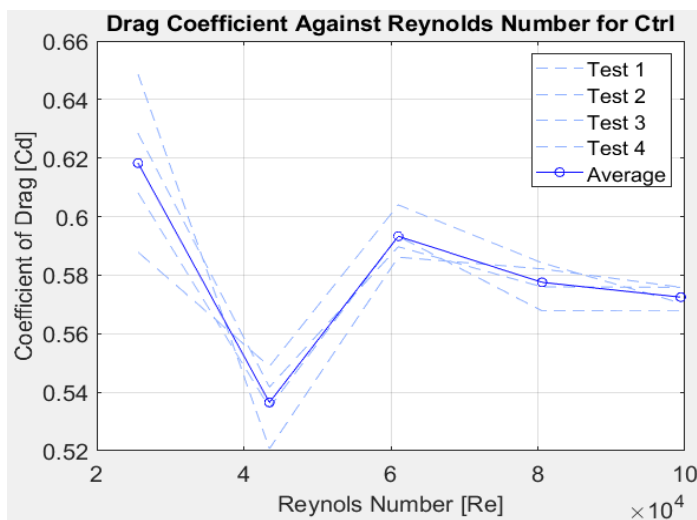


Figure 5.3-1: Top of Vortex's CAD model

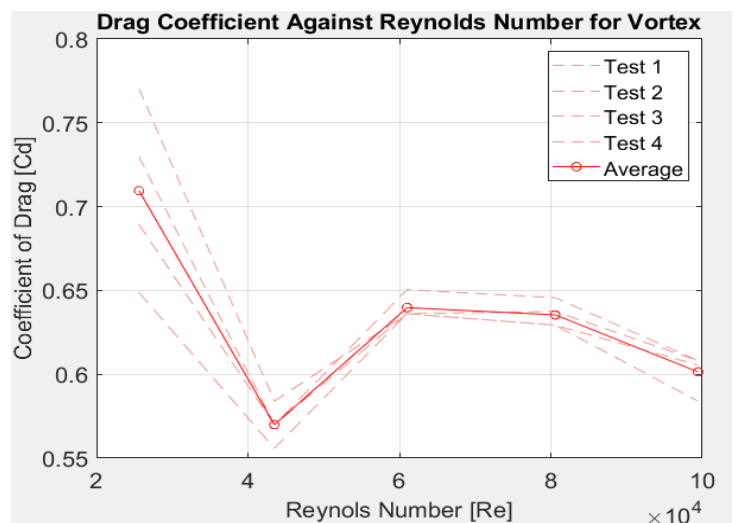
a. Vortex and Ctrl Cd against Re results:

The observed drag coefficient values for both rockets were plotted in Graph 5.3-1 for Vortex and Graph 5.3-2 for Ctrl. This was done to display the variation in the data collected and decide whether further investigation into the precision of the recorded results is necessary.

b. Ctrl against Vortex Cd-Re results:

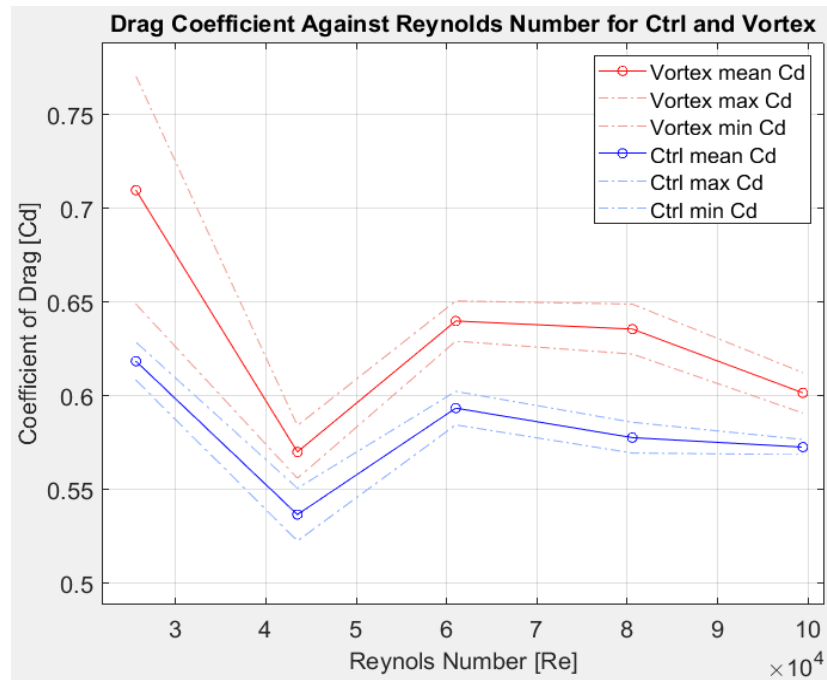


Graph 5.3-2: Drag coefficient against Reynolds number for Ctrl



Graph 5.3-1: Drag coefficient against Reynolds number for Vortex

The averaged drag coefficients of Vortex and Ctrl for each test point were plotted on Graph 5.3-3, in addition the the max and min values of Cd reached by each rocket. This was done to compare their drag coefficients.



Graph 5.3-3: Cd against Re for both Vortex and Ctrl

Repeatability of the wind tunnel tests run:

The repeatability of wind tunnel testing on both rockets was assessed. And that was done throughout testing each rocket 4 times at fixed time intervals. The precision study was run to test the accuracy of the results obtained.

Repeatability is used to set the minimum variation limit, repeatability studies are done for fixed factors which are:

- The experimenter.
- Equipment and tools used.
- Calibration of the facilities used.
- Environment (Temperature, Humidity and Pressure).
- The time between measurements and experiments.

Standard deviation is used to measure the amount of variation and dispersion of a set of values. Lower and upper limits were used to set the max and min acceptable variation in the collected data. They were calculated in accordance with BS ISO 5725 for 95% (*Management Systems Sector Board, 1995*). The equations used were as follow:

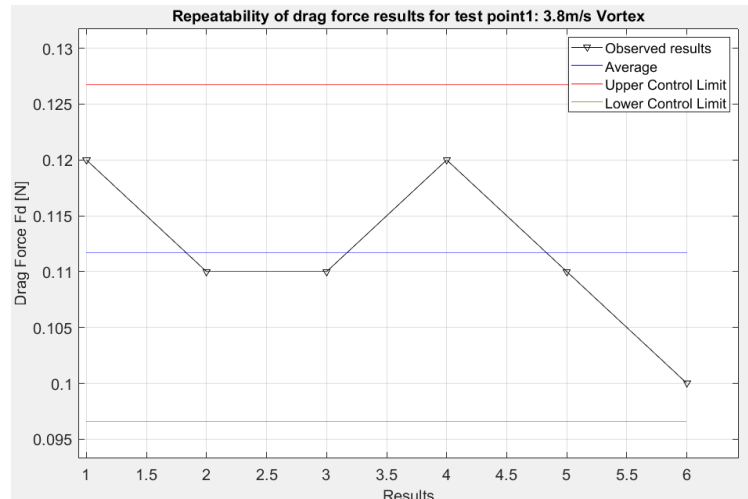
$$UCL = \mu + 2\sigma$$

$$LCL = \mu - 2\sigma$$

Graphs of lower and upper control limits were plotted for test points with high standard deviation value.

Test point '1' 3.8 m/s for Vortex:

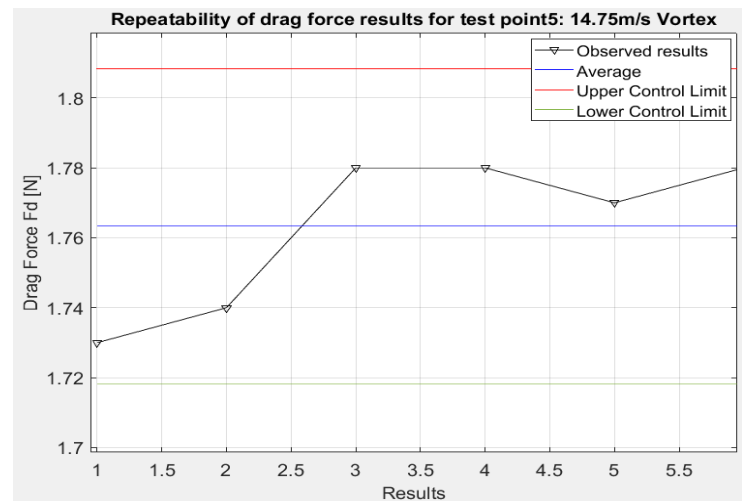
Error! Reference source not found. was plotted for the purpose of assessing the veracity of the results recorded for drag force. This specific point was targeted because it displaying a large variation in the drag coefficient from Graph 5.3-2**Error! Reference source not found.**



Graph 5.3-4: Mean chart of F_d obtained at test point 1 for Vortex

Test point '5' 14.75m/s for Vortex:

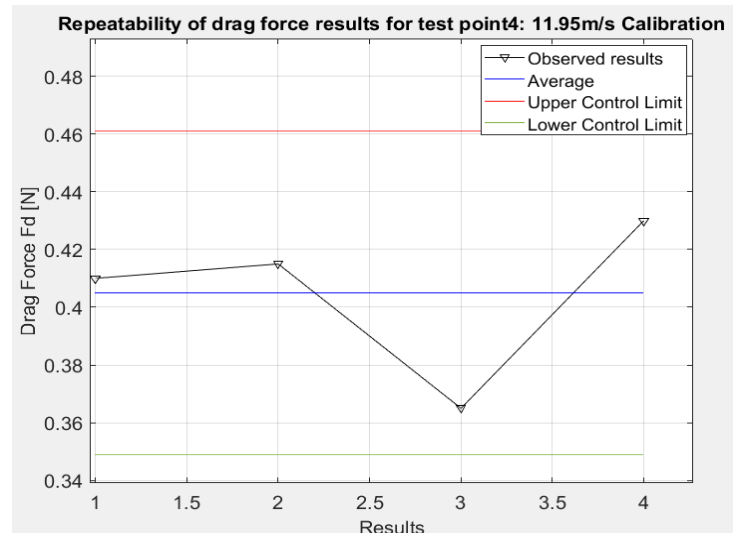
Graph 5.3-5 was plotted after perceiving that the standard deviation for test point '5' was the highest observed out of all Vortex tests.



Graph 5.3-5: Mean chart of F_d obtained at test point 5 for Vortex

Test point '4' 11.95m/s for Calibration of the mount:

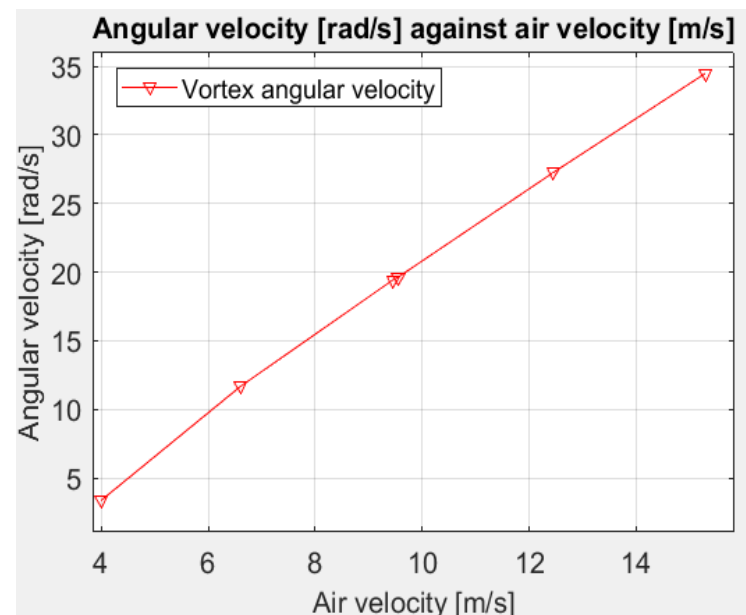
The test point with the highest variation in results for the mount, corresponding with test point '4', was assessed for repeatability and its UCL and LCL were calculated and plotted on Graph 5.3-6.



Graph 5.3-6: Mean chart of F_d obtained at test point 4 for the fixture calibration

c. Vortex angular velocity:

Vortex's angular velocity was plotted against the air velocity as shown in Graph 5.3-7. This was done to identify how the angular velocity varies with the increase in air velocity and expose potential trends.



Graph 5.3-7: Angular velocity [rad/s] against air velocity [m/s] for Vortex

5.4 Discussion and Analysis:

Drag Ctrl vs drag Vortex:

The drag coefficients of Vortex and Ctrl were not the same despite their cross-sectional area being identical. In fact, Vortex was subject to slightly higher drag forces than Ctrl. The drag forces recorded on Vortex were 3% (test point 5) to 13% (test point 1) higher than the drag forces observed on Ctrl.

The variation in drag coefficient ranged from 5% observed at the last test point and 17% in the first test point for Vortex. In the case of Ctrl, the drag coefficient ranged from 10% to less than 1% between Test point 1 and the last test point respectively. On both graphs

Graph 5.3-1 and Graph 5.3-2, it can be clearly observed that the variation in C_d decreases with the increase in Re . That can be related to the tools used not being precise enough for low velocities.

The dissimilarity in the drag experienced by the two rockets is due to the difference in the air flow around them. Indeed, Vortex was designed to spin and it hence creates vortices that increase its drag.

Other reasons to this variation could be:

- Imperfections on the rockets.
- Calibration values being erroneous.
- The rockets not being perpendicular to the face of the wind tunnel causing its cross-sectional area to be larger than calculated introducing errors in the collected data.
- The use of a hose clamp as a fixture for Vortex engendered a conflict in the forces acting on the rocket. Considering, the aerodynamic induced rotation is prevented by the mount holding Vortex which caused vibrations.

Data repeatability:

Despite the variation in the results obtained they all fell within the acceptability defined by the UCL and LCL. However, the precision of the LCL and UCL improves with the increase in the amount of data collected. Meaning, even though most values fall within acceptable results there is still a chance of them not being trustworthy as the BS ISO 5725 states that the precision increases with more tests done.

Angular velocity and V flow:

From Graph 5.3-7, it can be observed that the design of Vortex was successful in converting air flow into rotation. The angular velocity of Vortex increases in an approximately linear development at a rate of 2.25rad/m reaching a value of 34.49rad/s for an air velocity of 15.3m/s . Identifying the rate at which the angular velocity changes in relation to flow velocity is necessary in estimating angular velocity at points that are hard to test or even impossible to test due to limitations.

6. Chapter six: Video Analysis of Water Rocket Performance

To analyse the course of the rockets and estimate their velocities at launch Tracker®, a video analysis tool, was used. This software allows to track an object's velocity, displacement, and acceleration.

Tracker® assumption and limitation:

Tracker® is video analysis tool meaning it only considers two planes and hence does not take into account movement in the z axis (depth).

6.1 Materials and Software Used:

Table 6.1-1 bellow contains a list of the materials used for the purpose of the experiment.

Tool	Purpose	Model and reference	Range and accuracy
Video camera 1080p 240fps	Record footage of the rocket	One plus 7 Pro	-
Tripod	Provide stability for the camera	-	-
Protractor	Measure the angle at which the rockets were fired	Maped®	0-360 ° 1°
Rocket launcher	Launch the rockets	Rocket launcher fabricated by Finlay Hamilton	25-70 psi
A 1.65m individual	Used as a reference measurement	-	-
Electrical pump	Pressurize the air to a desire pressure	XIAOMI® portable electric air compressor MJCQB02QJ	3-150 psi ±0.1 psi
Tracker video analysis	Track the velocity, acceleration, displacement, and course of the rocket	Tracker Video Analysis and Modelling Tool©	-

Table 6.1-1: Materials and tools used for the rocket launching

6.2 Methodology:

Two testing methods were used. The first test, called Trajectory Test, was done for the purpose of recording the trajectory of the rocket. The Second test, Velocity Test, was done to measure the max height and max velocity reached by each rocket. Figure 6.2-1 shows how the rockets were set for both tests.

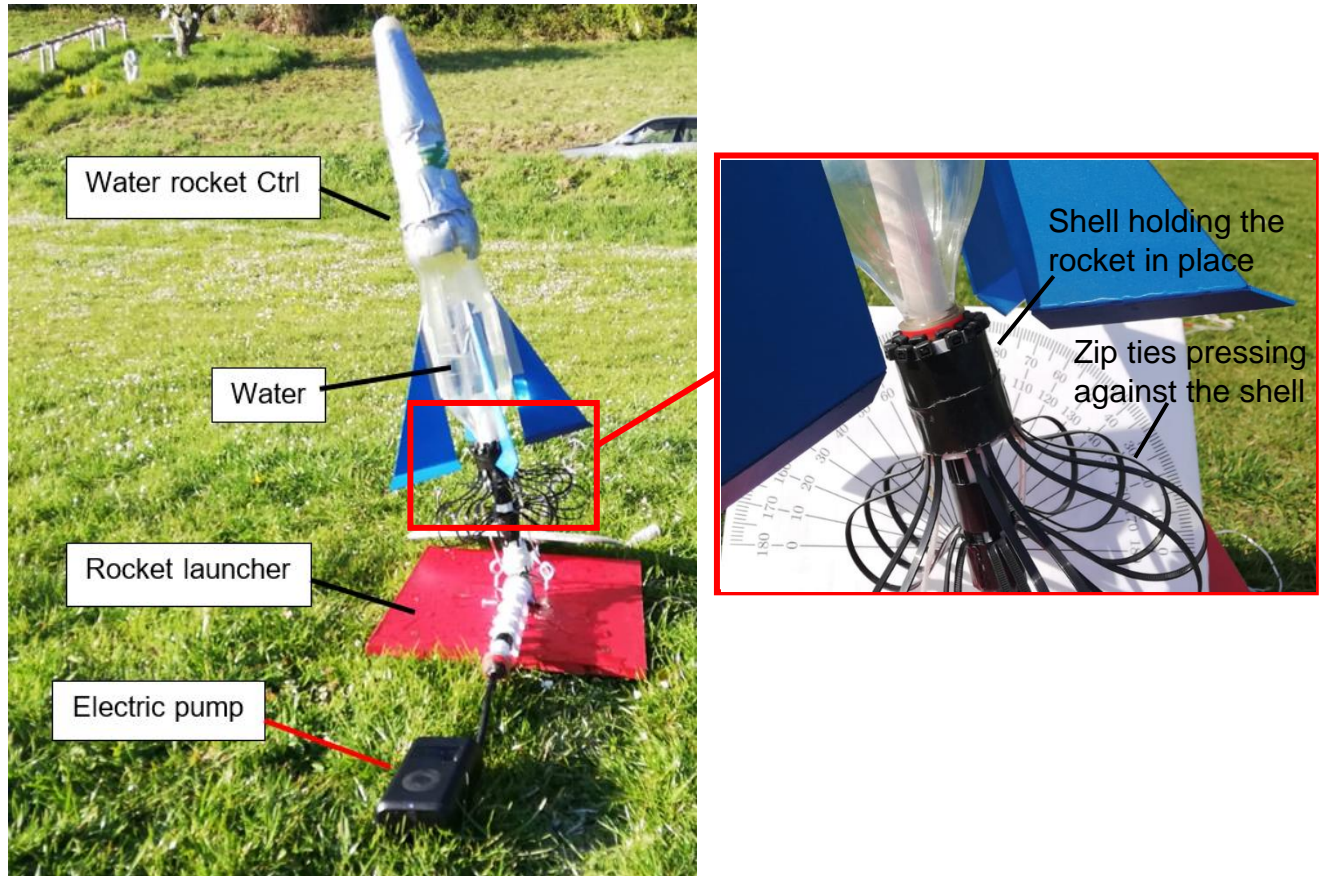


Figure 6.2-1: Water rocket launching setup

First test: Trajectory test

Recorded from a distance to allow capturing the whole rockets' course.

Second test: Velocity test

Recorded close to the rocket to get data on the rockets' velocities at launch.

Pre experiment setup:

- One side of a single fin on Vortex was painted a bright yellow to allow measuring its rotation.

The tripod was set at a fixed location to ensure all tests were run under the same circumstances.

Initial launching conditions:

Initial and ambient conditions of launching for both rockets were recorded as shown in Table 6.2-1 below:

Mass of the rockets	374g
Volume of water used	$1/3 V_{\text{Total}} = 0.58\text{l}$
Pressure	30psi = 206843Pa \pm 689.476Pa
Ambient pressure	1027mbar 1027 hPa
Ambient temperature	12°C 13°C
Humidity	54%
Wind velocity and direction	6m/s-7m/s from NE
Launching direction	Towards NE
Launching angle	$75^\circ \pm 2^\circ$

Table 6.2-1: Water rocket initial launching conditions

Launching steps:

1. The rockets were filled with 0.58l of water.
2. The rocket was slid on the PVC pipe and held in place using the zip ties pressing against the shell
3. The electric pump was then set to 30psi
4. Once the electric pump stops a signal to the cameraman is sent to start recording
5. The strings are then pulled to free the rocket

Video analysis:

Calibration:

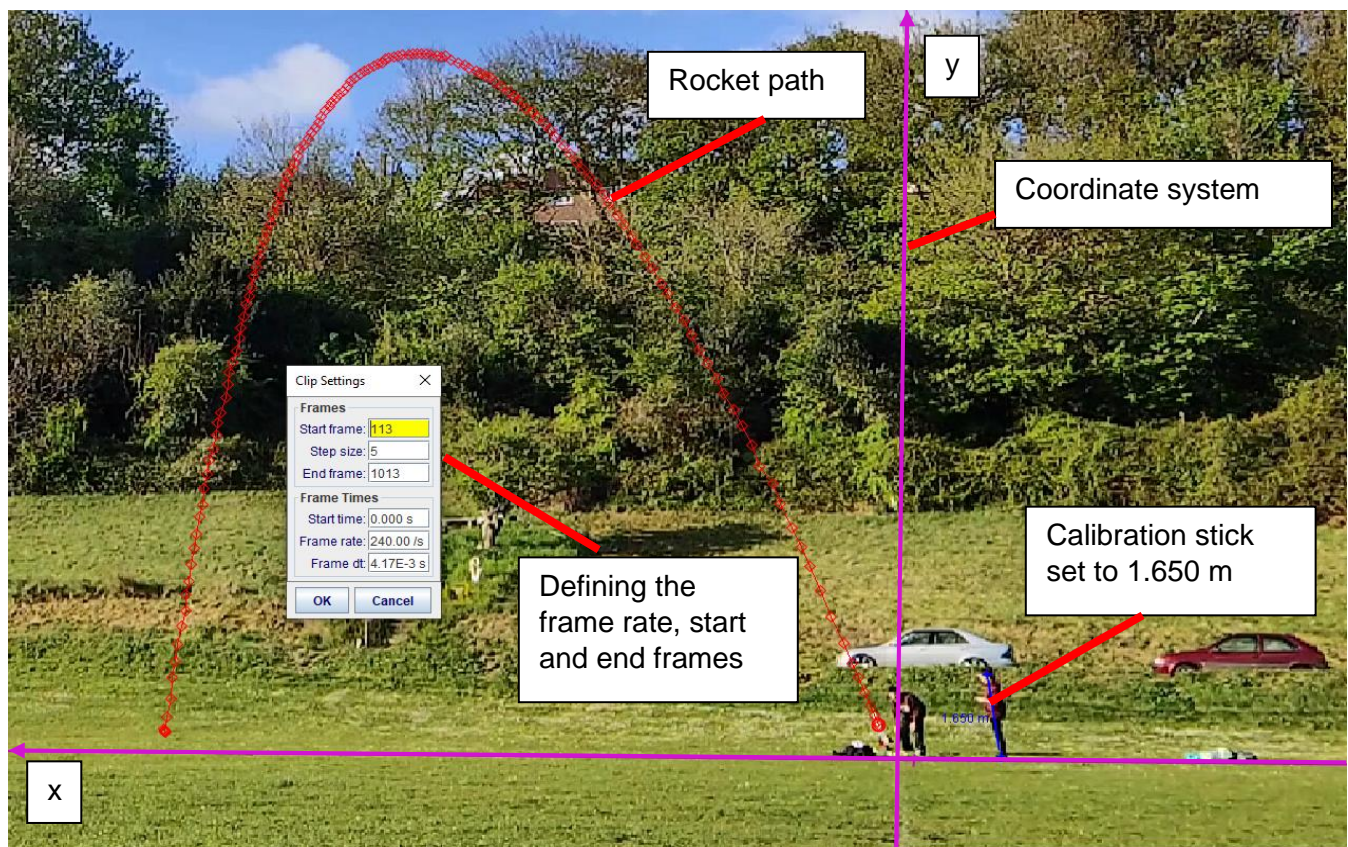
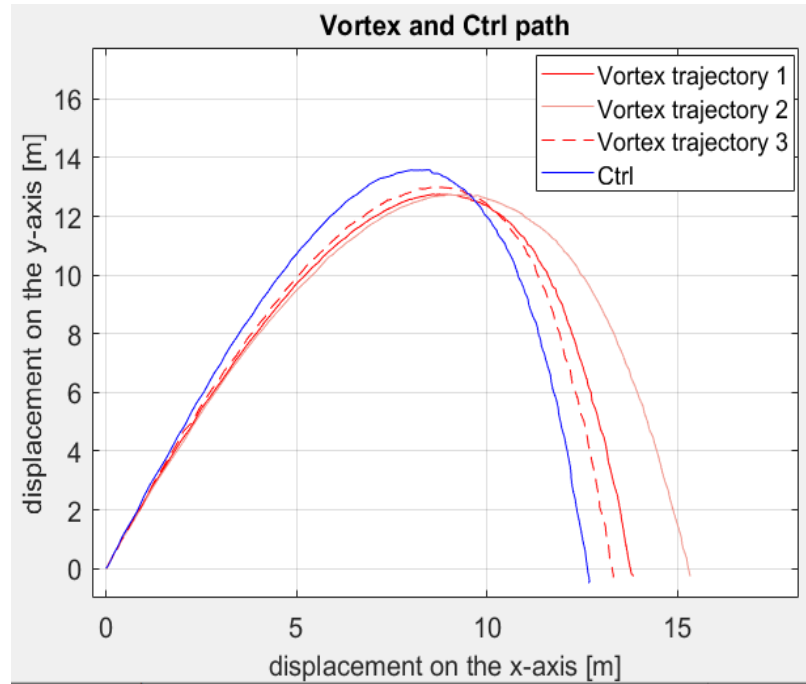


Figure 6.2-2: Tracker calibration and definition of initial parameters

6.3 Data and Results:

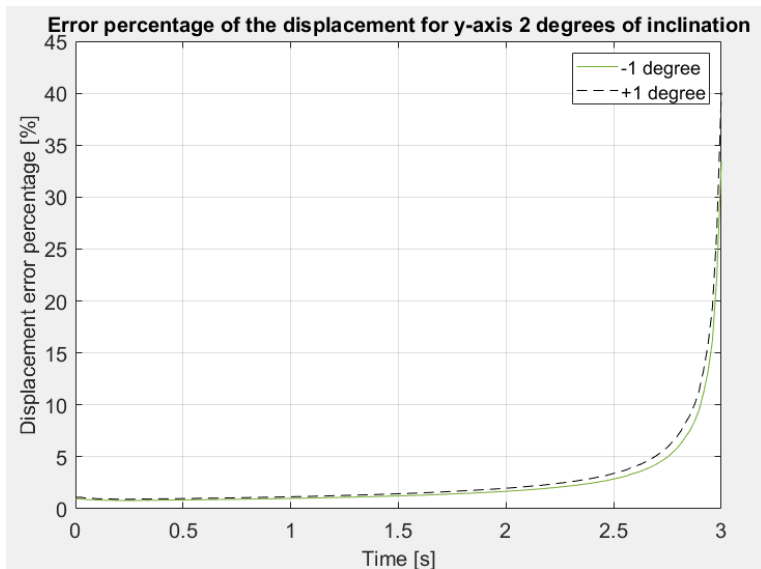
Path test results:

The path of the rockets for each test was plotted using data measured on Tracker. The Graph 6.2-1 displays the trajectories of both rockets.

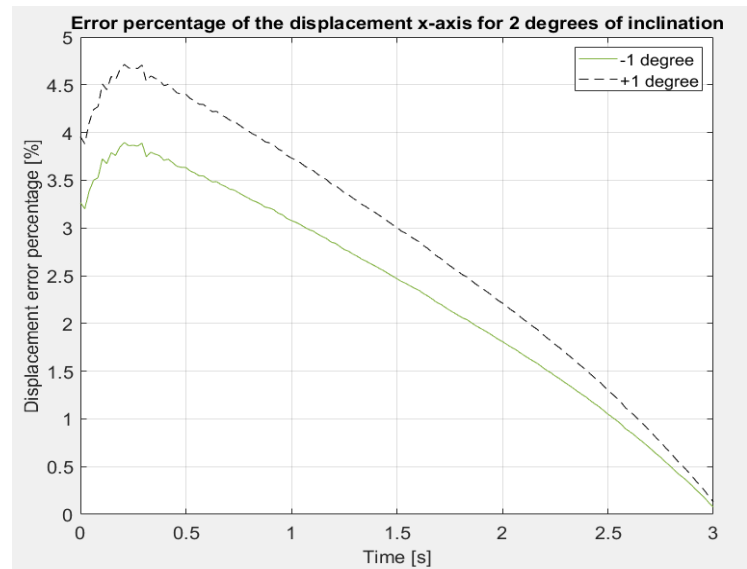


Graph 6.2-1: Vortex and Ctrl

In order to assess the effect inclination of 1 degree in the coordinate system has upon data produced by tracker, Graph 6.3-2 and Graph 6.3-3 were plotted.



Graph 6.3-2: Error percentage for displacement on Y-axis due to change in the coordinate system inclination angle



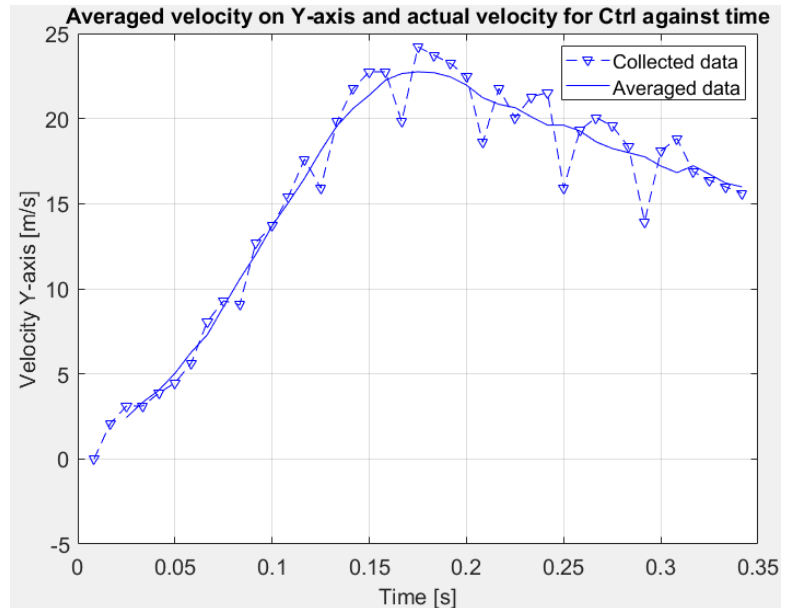
Graph 6.3-3: Error percentage for displacement on X-axis due to change in coordinate system inclination angle

Velocity test results:

Ctrl:

Graph 6.3-4 was plotted to display the effect of moving mean function from Matlab2021a on raw data. The function was used to obtain a better overview of the velocity trend.

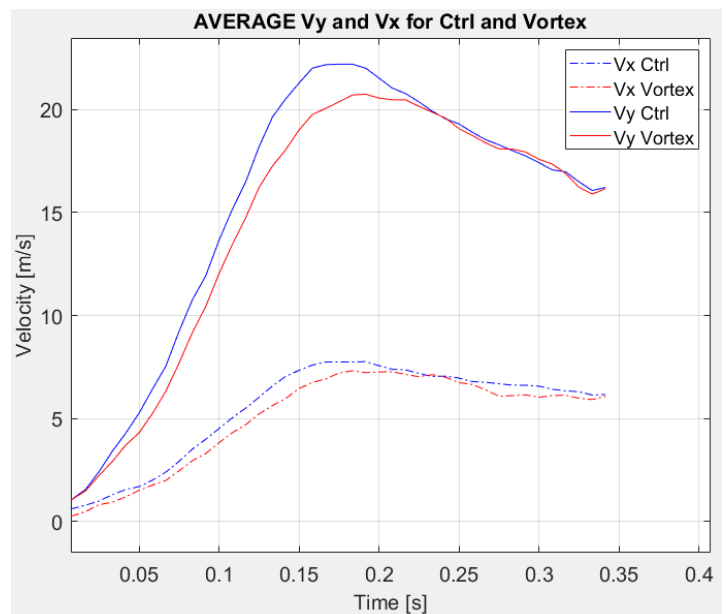
The fluctuations of velocity evident within the recorded data was speculated to be caused by the turbulent flow of the water leaving the nozzle.



Graph 6.3-4: moving mean function effect on raw data

Velocities recorded on each test for Ctrl
Velocities recorded on each test for Vortex:

Velocities on each axis for each rocket were plotted, as shown in Graph 6.3-5, to compare the x and y velocity components of both rockets.



Graph 6.3-5: Averaged Velocity on both X and Y axis for Ctrl and Vortex against time

From the literature review, Tracker's accuracy decreases as the camera distance increases. To why, the velocities recorded at launch of each rocket were used to calculate the max height reached. The time taken by each rocket from launch to landing was also recorded.

Calculating the max height reached by each rocket:

Assumptions:

- The drag coefficient of the rockets was assumed to be constant for all velocities (the value was taken to be the observed value from wind tunnel testing for the last velocity reached before the rocket left the screen)
- The cross-sectional area of the rocket facing the airflow was taken to be constant and equal to the one used during the wind tunnel tests.

Forces acting on the rocket after launch are:

$$\sum F_y = -F_d - W = ma_y \dots\dots\dots (6.3-1)$$

Θ : is the angle at which the rockets were fired, (1) becomes:

$$-W - F_d \sin(\Theta) = ma_y \dots\dots\dots (6.3-2)$$

By rearranging for a (2) becomes:

$$a_y = -\frac{W + F_d \sin(\Theta)}{m} \dots\dots\dots (6.3-3)$$

F_d is given by:

$$F_d = \frac{1}{2} \times A \times \rho \times V^2 \dots\dots\dots (6.3-4)$$

Where:

$$A = 0.01441771 \text{ m}^2, C_{d_{\text{vortex}}} = 0.605 \text{ and } C_{d_{\text{ctrl}}} = 0.575$$

And:

$$\rho = \frac{P_{\text{amb}}}{T_{\text{amb}} \times R} = \frac{102700}{285.65 \times 287} = 1.253 \text{ kg m}^{-3}$$

Displacement equation:

$$h_{\text{max}} = u_y t + \frac{1}{2} a_y t^2 \dots\dots\dots (6.3-6)$$

Time taken by the rocket to reach its max height is given by:

$$t_{\text{post launch}} = \frac{1}{2} t_{\text{total}} - t_{\text{launch}} \dots\dots\dots (6.3-7)$$

By substituting (6.3-7), (6.3-4) and (6.3-3) in (6.3-6):

$$h_{\text{max}} = u_y \left(\frac{1}{2} t_{\text{total}} - t_{\text{launch}} \right) + \frac{1}{2} - \frac{W + \frac{1}{2} \times A \times \rho \times u_y^2 \sin(\Theta)}{m} \times \left(\frac{1}{2} t_{\text{total}} - t_{\text{launch}} \right)^2 \dots\dots\dots (6.3-8)$$

For the distance travelled on the x axis:

$$\sum Fx = -Fdx = -Fd \cos(\theta) = \max \dots \dots \dots (6.3-9)$$

Rearranging 6.3-9 for acceleration on x:

$$a_x = -\frac{Fd \cos(\theta)}{m} \dots \dots \dots (6.3-11)$$

$$x_{\max} = u_x t + \frac{1}{2} a_x t^2 \dots \dots \dots (6.3-12)$$

By substituting (6.3-10), (6.3-7) and (6.3-4) in (6.3-12):

$$x_{\max} = u_x \left(\frac{1}{2} t_{\text{total}} - t_{\text{launch}} \right) + \frac{1}{2} - \frac{\frac{1}{2} \times A \times \rho \times u_x^2 \cos(\theta)}{m} \times \left(\frac{1}{2} t_{\text{total}} - t_{\text{launch}} \right)^2 \dots \dots \dots (6.3-13)$$

Table 6.3-1 and Table 6.3-2 below shows the calculated values using the equations mentioned above:

Rocket	$t_{\text{post-launch}}$ [s]	u_y [ms^{-1}]	h_0 [m]	a_y [ms^{-2}]	h_{\max} with drag [m]	h_{\max} without drag [m]
Vortex	1.411	15.200	5.557	-13.359	13.566	17.333
Ctrl	1.488	15.647	5.803	-13.374	14.121	18.2829

Table 6.3-1: Calculated data on both Vortex and Ctrl on the Y axis

Rocket	$t_{\text{post-launch}}$ [s]	u_x [ms^{-1}]	x_0 [m]	a_x [ms^{-2}]	x_{\max} with drag [m]
Vortex	1.411	5.926	2.04	-1.3436	14.063
Ctrl	1.488	6.254	2.2	-1.349	15.523

Table 6.3-2: Calculated data on both Vortex and Ctrl on the X axis

Table 6.3-3 below displays the observed values from tracker:

Rocket	Displacement [m]		Velocity [ms^{-1}]			Angular velocity	
	x-axis	y-axis	x-axis	y-axis		RPM	rads^{-1}
Vortex	13.678	13.000	7.643	21.515	22.801	327.87	34.334
Ctrl	11.804	13.585	8.329	23.674	25.02	0	0

Table 6.3-3: Observed rocket data

Table 6.3-4 was used to evaluate the difference between the calculated values using the velocity and the observed results from the trajectory test:

	Observed		Calculated		Difference calculated and observed	
	x axis	y axis	x axis	y axis	x axis	y axis
Vortex	13.678	13	14.063	13.566	3%	4%
Ctrl	11.804	13.585	15.523	14.121	24%	4%

Table 6.3-4: Table illustrating the percentage difference between the displacements on the two test methods

Table 6.3-5 was made to compare the results obtained by Tracker to the ones observed in wind tunnel testing for the angular velocity of Vortex.

	Velocity	Angular velocity		
	Averaged velocity	Tracker	Wind tunnel	error %
V vortex 2	15.075	34.15	34.41041767	0.8%
V vortex 1	16.7591	34.33	35.04116713	2.0%

Table 6.3-5: Comparison of the angular velocities recorded by Tracker and Wind Tunnel testing

6.4 Discussion and Analysis:

Both rockets performed as they were designed to, Vortex was spinning as wanted and Ctrl did not allow a single spin, meaning the design was successful on that regard.

Comparison of the displacement on both axis for calculated and observed data:

X axis comparison:

The calculated and observed values of the max displacement of both rockets on the x axis were different (3% and 24%) for Vortex and Ctrl, respectively as shown in Table 6.3-4. In addition, the max displacement calculated for Ctrl was much smaller than the observed value, 3.719m difference.

Reasons for the variation in addition to the ones mentioned in the Y-axis section:

- Change in cross-sectional area as the rocket transitions at its peak from ascending to descending.

Y axis comparison:

Max height calculated on the y axis for both rockets was expected to be higher than the observed value. In fact, from Table 6.3-4, the calculated values were found to be 4% higher than the results obtained from the trajectory test. These percentages are low

meaning that the data collected is trustworthy. The small variation was potentially caused by:

- Drag coefficient increasing for low speed (From the last point in the video the velocity of the rocket kept decreasing consequently increasing its drag coefficient and resulting in less distance travelled).
- Trackers assumption meant that drift in the z axis would not be accounted for and the max height would be incorrectly measured.

Comparison between Vortex and Ctrl:

Velocity comparison:

From the Graph 6.3-5 Ctrl had a higher overall velocity on both axes. That was due to its drag coefficient being smaller than Vortex and since both rockets have the same mass the weight of the rockets cannot have affected their performance.

Displacement on Y-axis:

Ctrl performed better than Vortex when it came to its displacement on the y-axis as shown in Graph 6.2-1. Indeed, the max height reached by Ctrl was 13.585 which is 0.585m higher than Vortex from Table 6.3-3. The results are justified by Ctrl having a smaller drag coefficient than Vortex observed in wind tunnel testing.

Displacement on X-axis:

Even though Ctrl had a higher velocity than Vortex, the latter reached 1.874m further on the x axis compared to Ctrl. Vortex smoothly transitions from ascent to descent through the effect of rotation, this ensures the cross-sectional area perpendicular to the direction of travel was kept constant as shown in Figure 6.4-1. Whereas Ctrl's non-linear change in path drastically increased its cross-sectional area causing a gain in drag.

This statement is consolidated by the low error percentage (3%), measured for the displacement of Vortex on the x-axis in Table 6.3-4, by comparing results obtained while assuming the cross-sectional area of Vortex was constant.

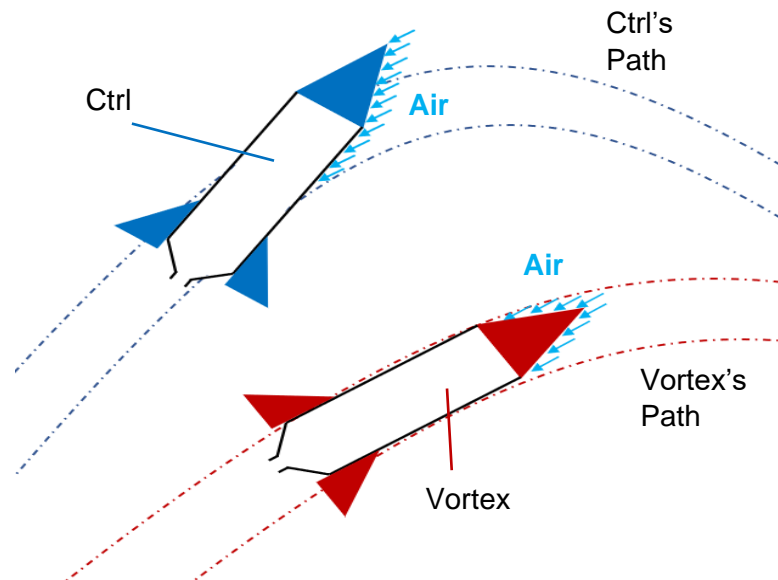


Figure 6.4-1: Diagram displaying the air acting on both rockets and their trajectory

Wind tunnel and tracker angular velocity comparison:

An averaged velocity for the recorded speeds of Vortex was used to identify which angular velocity to use from wind tunnel testing. With an error percentage of 0.8% and 2% as shown in Table 6.3-5, the values collected from Tracker© were close to the ones from the wind tunnel testing. Meaning the results are trustworthy and there is a correlation between the wind tunnel testing and the tracker analysis.

Results inaccuracies and test limitations:

From the graphs Graph 6.3-3 and Graph 6.3-2, rotating the coordinate system by 1° clockwise or anti-clockwise results in changes in displacement reaching up to 40% for distance travelled on the y-axis. In fact, the error percentage increases with time from 1% to 40% this matches the rocket travelling further from the centre of the coordinate system as shown in Figure 6.2-2. Whereas the percentage of error on the x-axis did not exceed 5%.

One major limitation and source of inaccuracy is the effect of wind on the trajectories of both rockets. It is very difficult to prove the trueness of the data collected because the wind does not blow at a constant rate and is hence unpredictable. In addition, Ctrl's fin broke during one of the tests resulting in the incapability of launching it repeatedly.

7. Chapter Seven: Conclusion and Further Work

7.1 Conclusion:

Many difficulties were faced throughout the project. One major difficulty was identifying what part of the project to specialize in as this led to delaying the project's advancement. One other difficulty faced was not being able to plan everything and the need to mitigate for different upcoming problems. The Gantt Chart was proven to be rather difficult to use for this project as the purpose and objectives kept changing. Plus, the project did not follow a chronological advancement and adjustments to the tasks were constantly needed. The dependency matrix was found to be helpful in preventing the obstruction of the project's development.

During this project, two rockets with different characteristics were designed and fabricated. The project has seen the production of a rotating rocket Vortex and a control rocket that interrupts rotation due to its aerodynamic properties. Furthermore, key points on rockets' stability were observed such as the importance of the mass distribution and having low fins to increase stability.

CFD simulation on SOLIDWORKS® was an accurate way of assessing the performance of the rocket when it comes to analysing the development of CD regarding airspeed. Moreover, SOLIDWORKS® simulations were found to be 3%-22% accurate compared to wind tunnel testing its accuracy was found to be increasing with higher Re. The software was also practical in evaluating the position of the CP for the rockets which is crucial to rocket stability.

Rockets with supposedly identical cross-sectional areas did not have the same CD. Through wind tunnel testing another factor affecting CD was identified, the latter is the flow around the rockets. Vortices created by Vortex increase the drag generated by the rocket.

The designed test rig was successful and achieved its goal by allowing rotation during wind tunnel testing.

Tracker was a great tool to analyse the rocket's performance, it gives a good overall idea of the path the rockets followed. Even though its accuracy decreased with the increase in camera distance, this was mitigated by having different camera setups and using various measured parameters from other tests (wind tunnel testing for an accurate value of drag coefficients used during the displacement calculations).

Objective achievement checklist:

Objective 1: Evaluate and research different accessible ways of assessing a rocket's performance.

Was achieved as various ways of assessing the rockets were identified and the whole project used only 3 key ways (CFD – Wind tunnel tests and Tracker) due to time limitations.

Objective 2: Design and fabricate water rockets utilising aerodynamics to induce or cease rotation.

Was achieved as two fully functioning rockets were produced. Both rockets were functioning as they were designed to and that was assessed through the analysis of the recorded videos during launch.

Objective 3: Assess the aerodynamics of water rockets using wind tunnel testing and CFD.

Was partially achieved. CFD simulations on drag coefficients for the final designs were not run. But for the wind tunnel test, many tests were done which increased the accuracy and the precision of the results. These were assessed following BS ISO 5725 instructions. Further work on the CFD can be done, such as evaluating the drag coefficient for both rockets at different velocities and simulating other scenarios.

Objective 4: Evaluate the performance of both water rockets using a video analysis tool.

Was partially achieved, more rigour can be implemented in the analysis of the videos. As Graph 6.3-3 and Graph 6.3-2 display the effect of a small change in the inclination of the coordinate system on the data collected hence consolidating the importance of correctly defining the coordinate system.

Objective 5: Conclude on the effect of rotation on water rockets and identify the limitations of the study and what potential improvements can be implemented.

Was partially achieved. The lack of Ctrl's trajectory data consequently made the data recorded not reliable, as more tests need to be done before making a final statement. The limitations of the study were identified and the improvements that can be done on each section of the project were clearly stated in the next section.

All in all, the study showed that the new design causes more drag than an average rocket. In addition, Vortex was found to be better at transition and sticking to its path than

Ctrl reaching higher distances on the x-axis. However, this study is not conclusive, considering many variables affect the collected data and further work is needed to make a final statement on the effect of rotation on water rockets.

7.2 Further Work and Improvements:

Planning:

Planning can be improved using a flow chart from the start. This tool is an excellent way of identifying each stage of the project and ensuring a logical development of the project.

Water rocket designs:

Vortex design can be improved through opting for a less drag inducing design that would also increase angular velocity such as the twisted fin design. This would be manufacturable if more time was available. Better materials could have been used during fabrication, such as LDF or hardened foam to reduce the mass of the fins. Hence reduce the mass of the tip required which would increase the max height reached. The use of a thinner bottle would decrease the drag coefficient for the fuselage of the rockets.

Simulations:

Simulating the flow around both final designs and comparing it with wind tunnel testing would have been a great way of confirming the observations from the prototype tests.

Wind tunnel:

More rigour could be implemented, use a tool to line up the rocket to be perfectly facing the wind tunnel to get more accurate results. Considering the humidity inside the wind tunnel testing room would also add more accuracy in comparing the simulations with the wind tunnel tests.

Video analysis:

Use a better camera with a higher resolution, this would ease identifying the centre of gravity of the rocket from a distance making its course and max height more trackable. Using clearer reference points to define the axis and calibrate the software would also be a great way in adding rigour to the video analysis process. One other way to improve the accuracy of the results obtained, is by testing the rockets in places with no wind such as inside a warehouse.

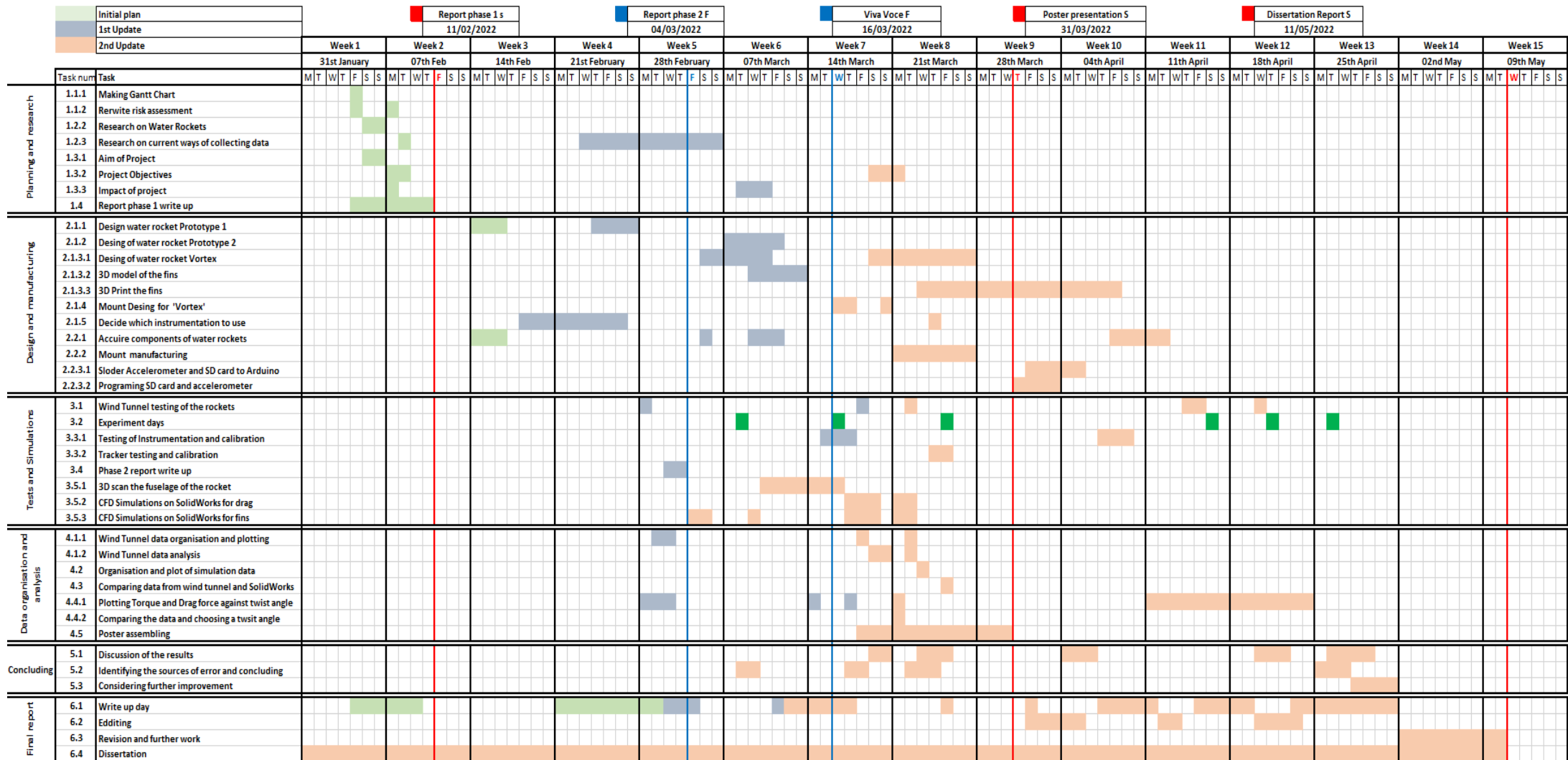
Further work would be to test designs that provide different angular velocities to get a better overview on the effect of rotation on water rockets

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Appendix 1: Gantt Chart



Appendix 2: Dependency Matrix

Task Number	1.1.1	1.1.2	1.2.2	1.2.3	1.3.1	1.3.2	1.3.3	1.4	2.1.1	2.1.2	2.1.3.1	2.1.3.2	2.1.3.3	2.1.4	2.1.5	2.2.1	2.2.2	2.2.3.1	2.2.3.2	3.1	3.2	3.3.1	3.3.2	3.4	3.5.1	3.5.2	3.5.3	4.1.1	4.1.2	4.2	4.3	4.4.1	4.4.2	4.5	5.1	5.2	5.3	6.1	6.2	6.3	6.4	
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3.3.2																X																										
3.4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																			
3.5.1																X																										
3.5.2										X	X																															
3.5.3											X																															
4.1.1																X	X			X																						
4.1.2																X	X			X									X													
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4.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																			
5.1																																										
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6.1	X	X	X	X	X	X	X	X																																		
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6.3																																										
6.4	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	X	X	

Appendix 3: Risk Assessment

Resource and general factors risk assessment							
ID	Resource	Risk	Severity (1-3)	Likelihood (1-3)	Risk Factor (1-9)	Risk Level (Low, medium/high)	Mitigation
Risk associated with software							
1	Ansys CFD	cannot install the software on your PC, Not having a license	3	1	3	Low	Get a stronger pc or use the University ones and back the files. Try find similar studies already done. Simulate using different software
2	MATLAB	Not having a license	3	1	3	Low	Use the University PC or get to do it on someone else PC/laptop a friend's or another student's.
3	Microsoft Office 365	Not having a license	3	1	3	Low	Use the University PCs or ask for a license key by emailing the IT team.
Risk associated with hardware, equipment							
4	Wind Tunnel	Not having access to the facility (Covid reasons or overbooked). Getting the wrong results because the rocket was not attached properly.	1	2	2	Low	Book in advance Try find similar studies already done. (Covid) Simulate using different software. Making sure all the instructions on how to use the wind tunnel are followed and run test on SolidWorks to confirm that the results are acceptable.
5	3D Printing machines	Not having access to the facility due to lock down or the printers being overbooked	1	2	2	Low	Book in advance or find an alternative such as trying to manufacture the case using wood or at worse buy a case from a manufacturer.
6	Soldering	Not having access to the University lab and equipment.	2	1	2	Low	Make sure to book in advance. Or buy own soldering equipment or get one from a friend or other students.
7	Laser cutter	Not having access to laser cutter (over booked)	1	1	1	Low	Book in advance, make own fins using carboard or other material.
8	Laptop	Laptop stops working	3	1	3	Low	Use the university PC and make sure to back up files.
Risk associated with general factors about the project,							
9	Communication with supervisor	Not being able to contact or meet with supervisor.	2	2	4	Medium	Use teams to meet online, try dropping emails or meeting in the office. Ask other lecturers for advice.
10	Health issues	Catching covid or getting other diseases	2	1	2	Low	Make sure to plan things in advances and leave room for unpredictable. To reschedule and finish the project on time. If it is enough apply for mitigating circumstances.

Risk assessment on using different facilities								
No.	What are the hazards?	Who might be harmed and how?	What controls do you already have in place?	Risk (H/M/L)	What further action is necessary to reduce the risk to Low?	Action by whom?	Action by when?	Done
i	Risk assessment during the water rocket launching experiment							
1	Water rocket falling or flying into someone	Student and may be people around if done in open areas	Set the angle of the water rocket to be at least 45 degrees from ground. Carry experiments in open areas like a park with a lot of clearance. Keep an eye on the rocket to see where it will land.	M	Making sure to check the wind to know where the rocket will land hence avoiding injuring people	Student and participants	During the experiment day	yes
2	Tripping or running over either backpacks or the components of the water rocket (wires)	Student and may be people around if done in open areas	Gathering all the backpacks into one spot where all the bits and pieces can be put. Making sure the components of the rocket are not spread everywhere.	L	Minimise the components of the rocket having shorter wires and smaller water containers	Student	Experiment day	yes
3	Rocket hitting aircraft	Student and participants debris falling	Making sure the area is clear before launching the rocket	L	Avoiding the plane trajectory / path	Student	Experiment day	yes
4	Slipping hazards	Student and participants. Trip or slip-on wet floor and get injured by falling	Making sure the floor is dry and that there are no leaks	M	Being careful when using the water. Do the experiment in a park where wet floors are not that dangerous	Student and participants	Experiment day	yes
5	Damaging properties and the environment	Properties (buildings around)	Making sure the rocket is not pointing at buildings. Putting a wooden plate to avoid damaging the ground in parks	L	Set the experiment in open spaces with no buildings around	Student	Experiment day	yes
6	Water rocket blowing up	Student	Making sure the pressure of the air is not too high not exceeding 3atm. Make sure to use a pin to launch the rocket from a safe distance.	M	Making sure the rocket is made of strong components and that there is no leaks and everything is taped properly	Student		yes
ii	Risk Assessment for using the wind tunnel							
6	Flying objects or debris that leave the test stand	Injure the student carrying out the test	Making sure to keep all objects away from the wind tunnel (store them in lockers before to start the experiment)	H	Use a net and other debris catching tools	Student	During the test	yes
7	Noise hazard Hearing loss or tinnitus	Injure the student carrying out the test	Use ear plugs	M	Leave the room if the noise is not bearable	Student	During the test	yes
iii	Risk Assessment when soldering own PCB							

8	Burning due to soldering	The student who is soldering	Make sure to get training before using the soldering iron.	M		Student	During the labs	yes
9	Cuts or hurting self while pulling the plastic of the wires	The plier user	Be careful when using the pliers when trying to remove bits of the wires. Makes sure to pull the plastic bits away from the body and not towards the face.	L		Student	During the labs	yes
10	Inhaling hostile gas Cause irritation and respiratory tract irritation (especially when using lead)	The person who is soldering	Stay away from the fumes.	M	Leave the room to get fresh air every 10min to minimise the effect of the hazardous fumes. Cleaning hands after soldering.	Student	During the labs	yes
11	Burning hair or bracelets getting caught on material	The person who is soldering	Attach hair and avoid wearing bracelets or necklaces	L		Student	During the labs	yes
iv	Risk assessment when using the laser cutter							
12	Burns	The user	Make sure to keep the laser cutter covered and under no circumstances use the laser cutter without receiving training	M		Student	During the lab	yes

Signature from student

Signature from supervisor

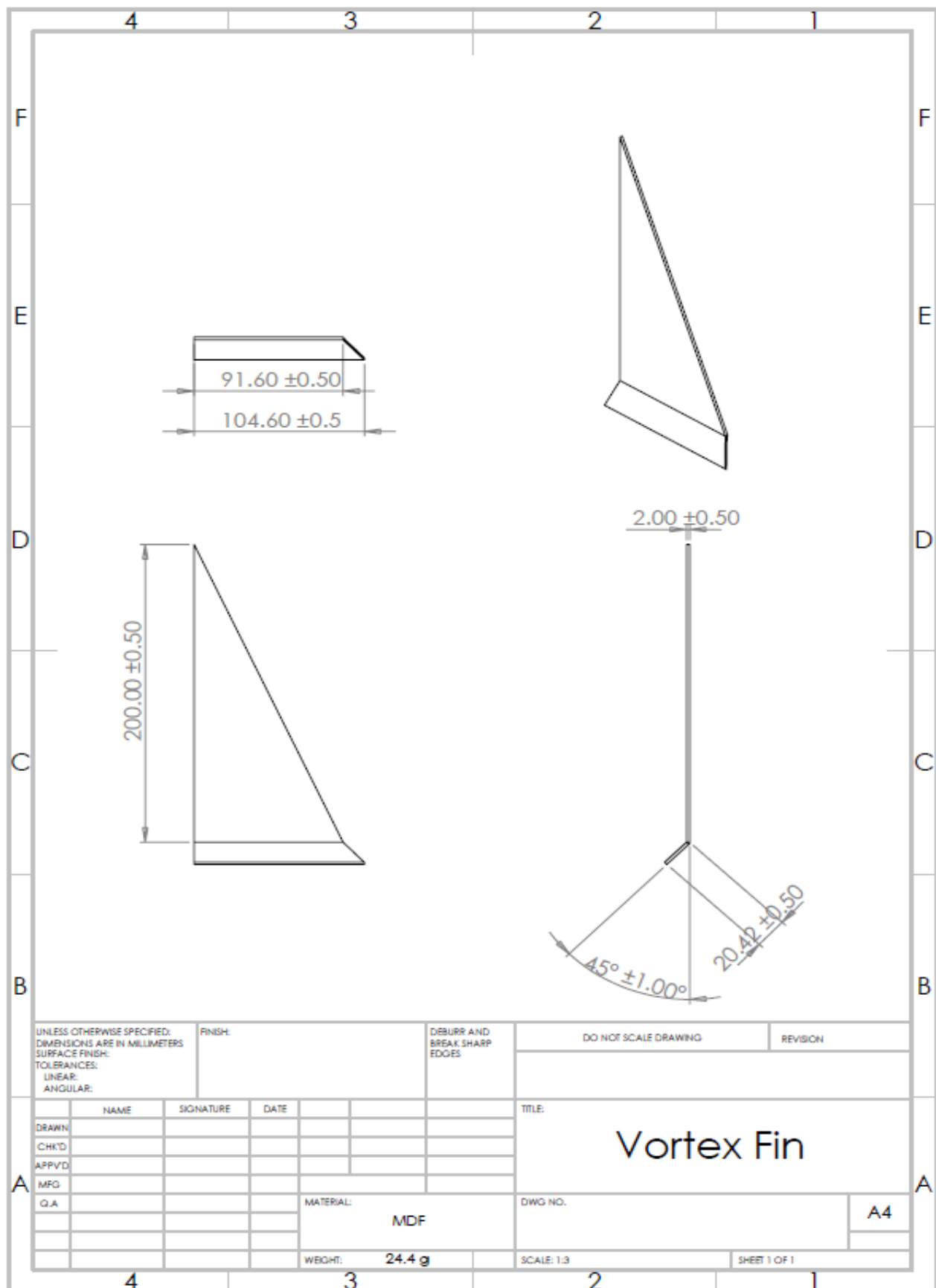
Lydia Beniken

Ethical review:

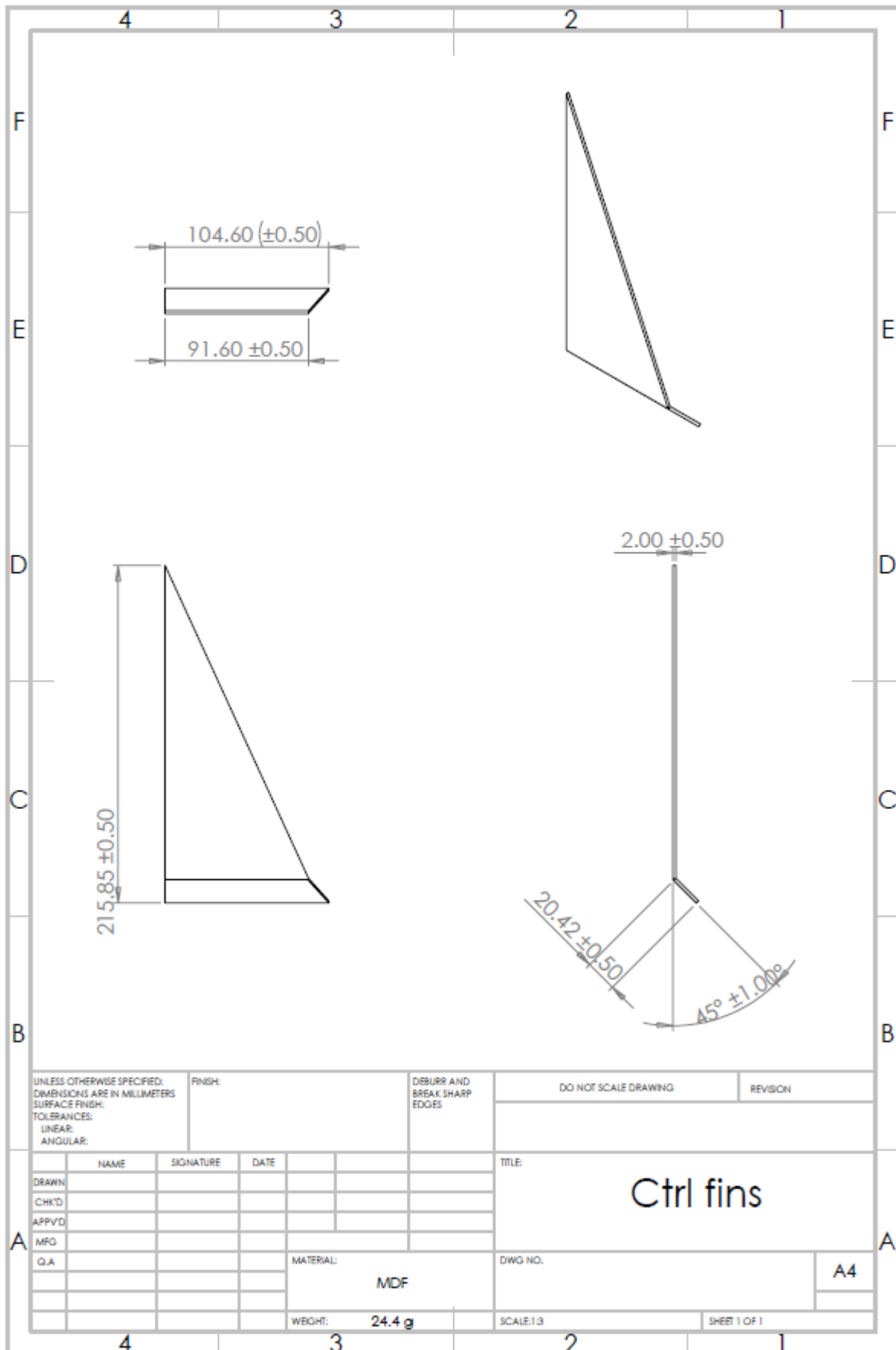
	Question	Yes	No
1	Will the project involve the participation of humans (eg interviews, surveys, focus groups, observations, photography, audio or video recording, physical activity or invasive/intrusive procedures)?		x
2	Will the research involve the use of bodily materials derived or obtained from humans?		x
3	Will the research require access to, collection of or use of personal human data or property (personal data is data about a person from which they could be identified)?		x
4	Will the research require access to, collection of or use of (non-personal) sensitive or confidential data?		x
5	Does the research have the potential to expose any person, whether or not participating in the research, to physical or psychological harm?		x
6	Does the research have the potential for significant negative impact on or damage to the natural environment?		x
7	Does the research have the potential for significant negative impact on culture or cultural heritage?		x
8	Will the research involve the use of or study of animals of any kind? (Note: animal research should be reviewed by the Animal Welfare and Ethical Review Board).		x
9	Are there any other ethical issues raised by this research project that in the opinion of the applicant would warrant ethical review?		x

Appendix 4: Engineering drawings

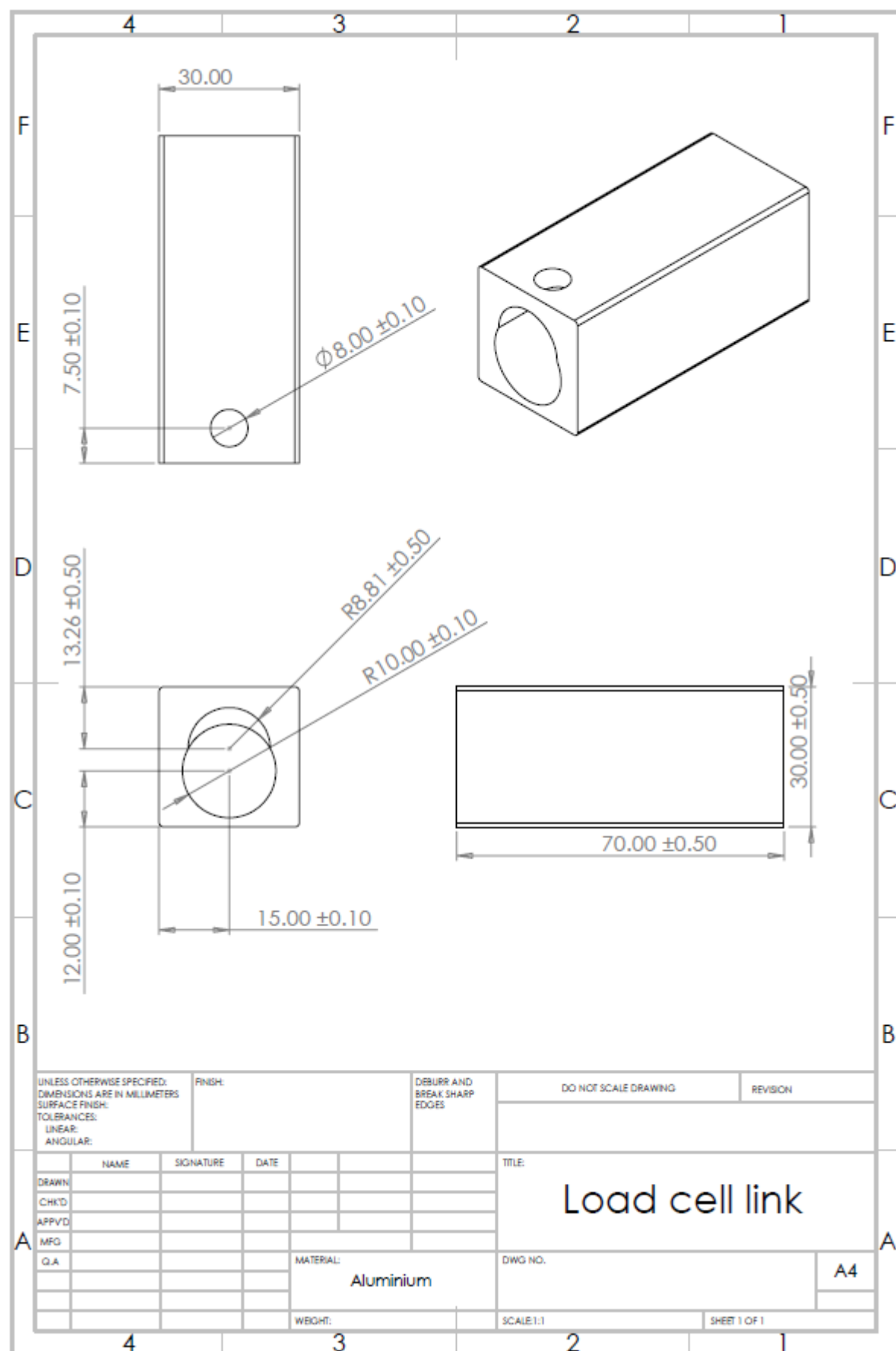
Vortex fin technical drawing:



Ctrl fins engineering drawing:



Aluminium link to load cell:



Appendix 5: Rocket kits pricing

Research on the cost of current available rockets was done to have an estimation on how much the rockets should cost to manufacture. The results are shown in Table 0-1 below

Rocket kit model	Price including VAT and shipping	Provider
4M- 4385 - Science in Action Water rocket	21.99	Amazon
PLAYSTEM Water Rocket Launcher kit with rocket tail, Body, and Pump DIY Rocket Science Experiment Kit- Space STEM Outdoor Toys Gift for Kids, Teens, Boys and Girls	29.99	Amazon
ROKit Bottle Rocket Water Pressure Kit, Pump Action	20.75	Amazon
ROKIT Water rocket kit	14.98	Amazon
Average price of a rocket	21.93	

Table 0-1: List of current rocket kit product and their prices