Department of Aerospace Engineering
Indian Institute of Technology Bombay

STRUCTURAL DESIGN AND ANALYSIS OF MODEL ROCKET

AE238 COURSE PROJECT: AEROSPACE STRUCTURAL MECHANICS

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System Overview

Introduction to Amateur Rocketry

Amateur Rocketry or experimental rocketry is a hobby of building and launching small scale rockets which was popularised in the late 1950s and early 1960s following the launch of Sputnik, the world's first artificial Earth satellite. Since then the hobby has developed a lot and many complex systems used in actual rockets are being used in model rockets.

Mission Statement

Build a single stage model rocket designed to reach an apogee of **150m** using standard easily available components and COTS E class model rocket motors**.** The rocket should have a flight computer which performs basic functions like data logging for post-flight analysis and deployment of recovery systems.

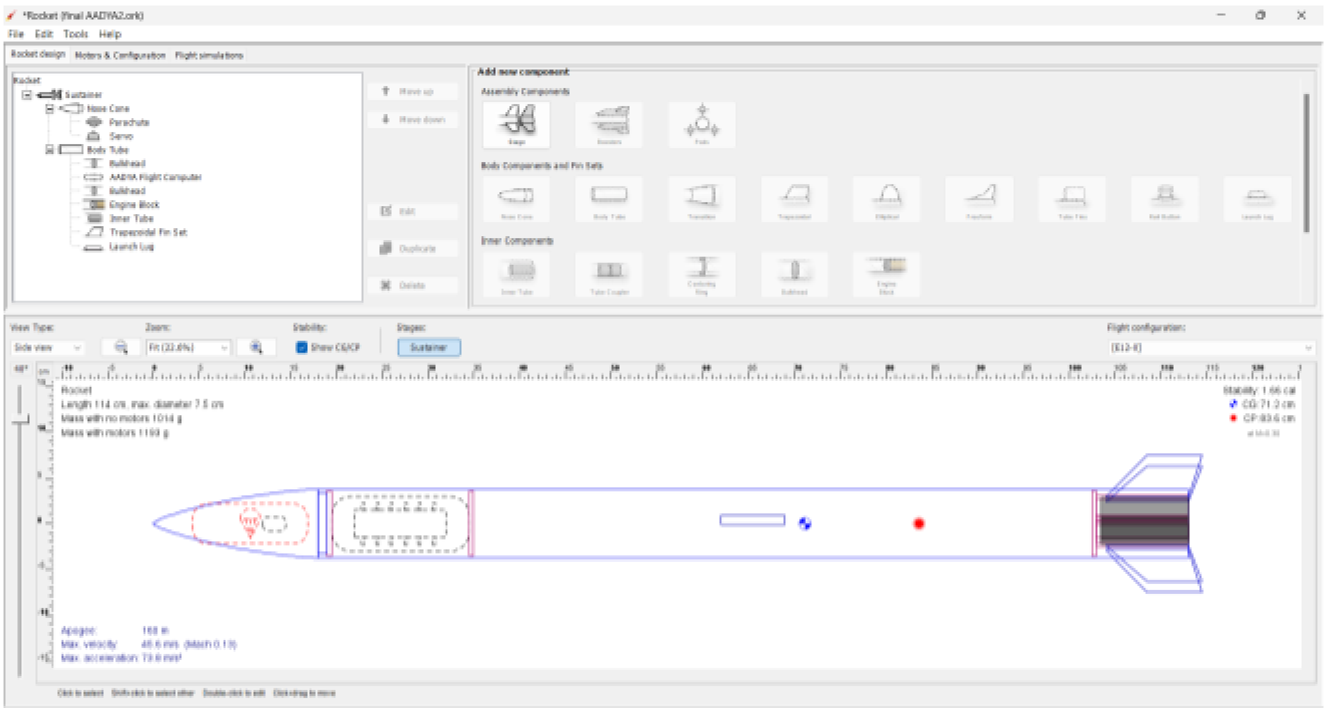
Systems

- Mechanical
  - Structural Design, Analysis and Fabrication
    Designing the nose cone, fins and other structural components of the rocket and manufacturing these parts using suitable methods
  - Integration of the various parts
- Electrical
  - Developing a flight computer to perform data logging and recovery systems deployment
  - PCB with Raspberry Pi Pico and various sensors like 6–DOF IMU MPU6050 to determine the attitude of the rocket, Absolute Pressure and Temperature sensor BMP280 for estimating the apogee altitude.
  - The data will be logged into a microSD card which will be retrieved post-flight for analysis
- GNC
  - Exploring active stabilisation methods like fin actuation and thrust vectoring to improve the passive stability provided by fixed fins
- Recovery
  - Designing the parachute using suitable material, dimensions, spill hole, no. of shroud lines, etc.
  - Ensuring the proper fitting of the folded parachute into the body tube and deployment using firing of the deployment charge

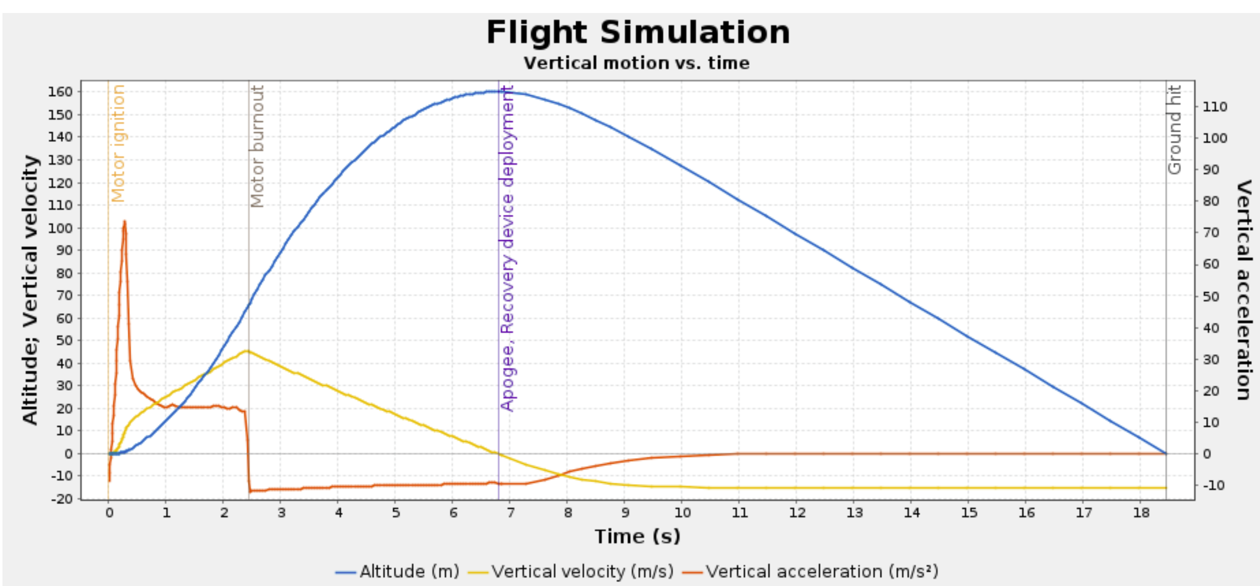
In this report we will be focussing only on the Structural aspect of the Rocket considering the other systems like the flight computer and recovery system to be just mass components

We designed our rocket using **OpenRocket** which is a widely acclaimed open source model rocket simulation software

OpenRocket v22.02



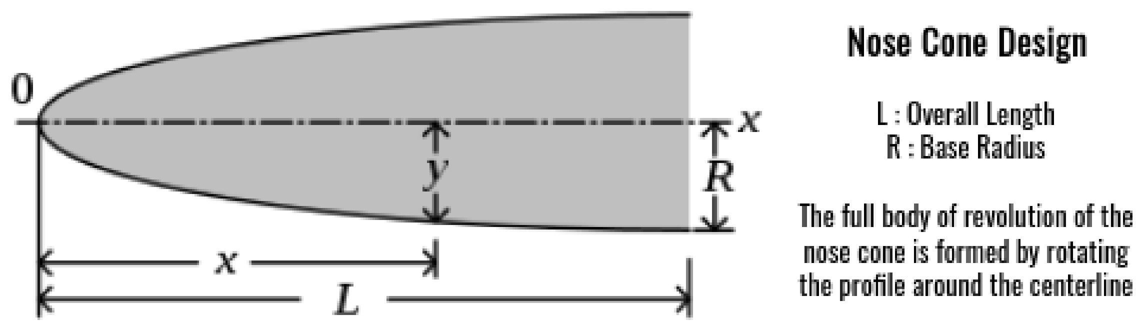
OpenRocket UI

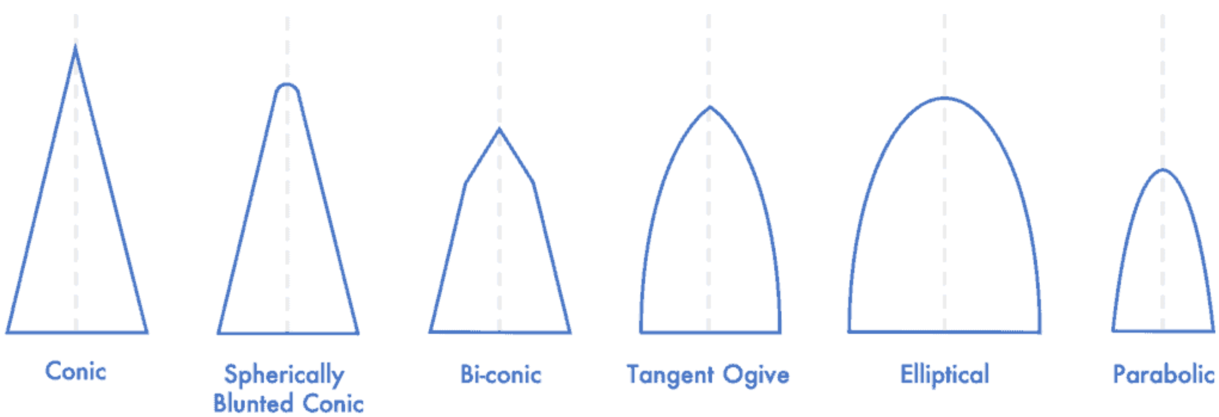


Structures in Rockets

Nose Cone

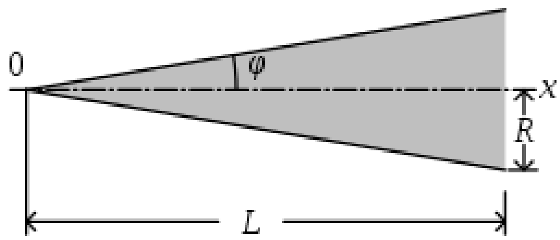
Nose cone is the forwardmost section of the rocket designed to module oncoming airflow and minimise aerodynamic drag. Given the problem of the aerodynamic design of the nose cone section of any vehicle or body meant to travel through a compressible fluid medium, an important problem is the determination of the nose cone geometrical shape for optimum performance. For many applications, such a task requires the definition of a solid of revolution shape that experiences minimal resistance to rapid motion through the fluid medium.





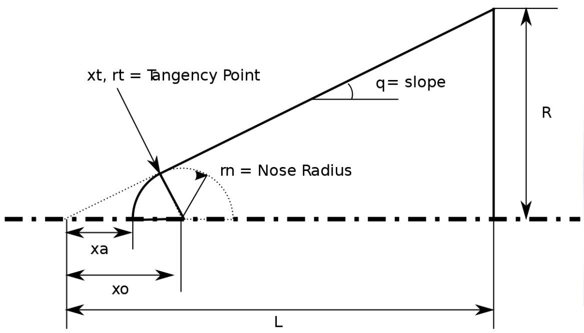
Types of Nose Cone Geometries

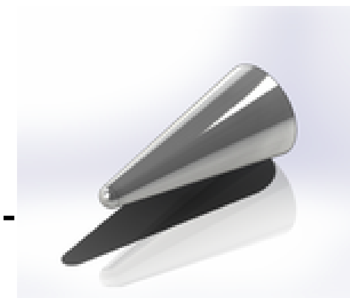
TYPES OF NOSE CONES



CONIC

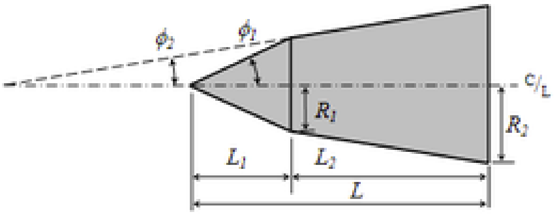
Easy to manufacture as compared to the streamlined shapes

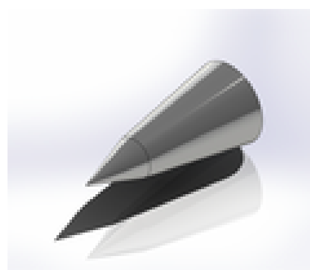




SPHERICALLY BLUNTED CONIC

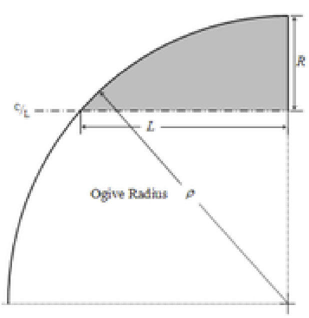
Used in re-entry vehicles for hypersonic flow for thermodynamic reasons

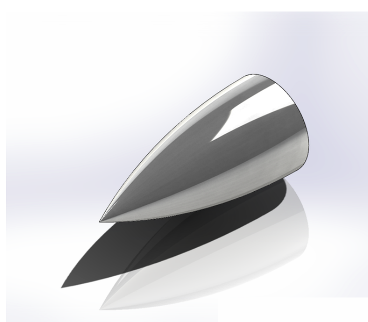




BICONIC

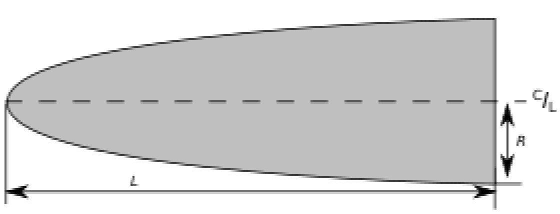
A bi-conic nose cone shape is simply a cone stacked on top of a frustum of a cone (commonly known as a *conical transition section* shape)





TANGENT OGIVE

the most familiar in hobby rocketry. The profile of this shape is formed by a segment of a circle such that the rocket body is tangent to the curve of the nose cone at its base, and the base is on the radius of the circle.



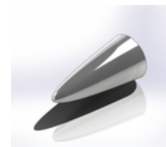
ELLIPTICAL

This shape is popular in subsonic flight due to the blunt nose.

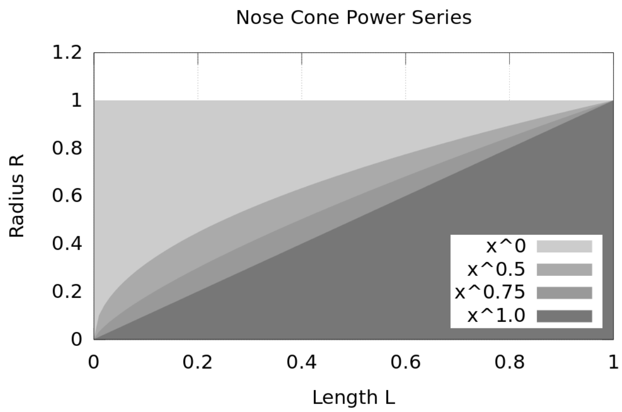
POWER SERIES

The power series shape is characterised by its (usually) blunt tip, and by the fact that its base is not tangent to the body tube. There is always a discontinuity at the joint between nose cone and body that looks distinctly non-aerodynamic. The shape can be modified at the base to smooth out this discontinuity. Both a flat-faced cylinder and a cone are shapes that are members of the power series.

$$y = R\left(\frac{x}{L}\right)^n$$



n	Power type
0	Cylinder
1/2	Half (Parabola
3/4	Three Quarter
1	Cone

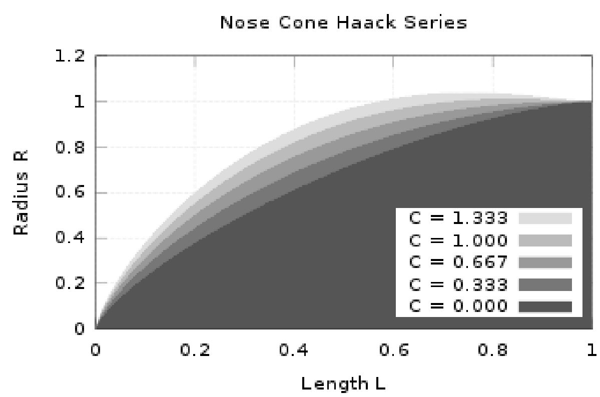


HAACK SERIES

Unlike all of the nose cone shapes above, Wolfgang Haack's series shapes are not constructed from geometric figures. The shapes are instead mathematically derived for the purpose of minimising drag. Von Kármán nose cone gives minimum drag for given value of length(L) and diameter (D).

$$\theta(x) = \arccos\left(1 - \frac{2x}{L}\right)$$

$$y(\theta, C) = \frac{R}{\sqrt{\pi}}\sqrt{\theta - \frac{\sin(2\theta)}{2} + C\sin^3(\theta)}$$



Haack Series Type	C
LD-Haack (Von Kármán)	0
LV-Haack	1/3
Tangent	2/3

Our CAD model of Von Kármán nose cone

Body Tube

The main airframe of the rocket contains the payload, flight computer, recovery system, motors.

Can be made of a variety of different materials ranging from cardboard, PVC to fibreglass and carbon fibre

Bulkheads

Bulkheads form an impenetrable block between two sections of a model rocket--typically, the section with the recovery device, and a payload bay. The shock chords of the parachute are attached to the bulkhead.

Motor Mount

Motor mounts are used to position an engine tube into a larger model rocket airframe. In order to secure the motor in place during flight a motor mount is required. The motor mount must be designed to locate the motor within the skin tube, as well handle the thrust force caused from the motor. Since the rocket mount is located between the skin and the rocket, both the inner and outer diameters are restricted and must be considered during the design phase

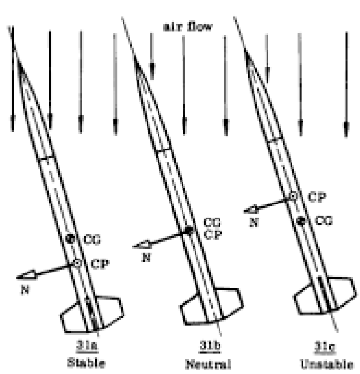
Avionics Bay

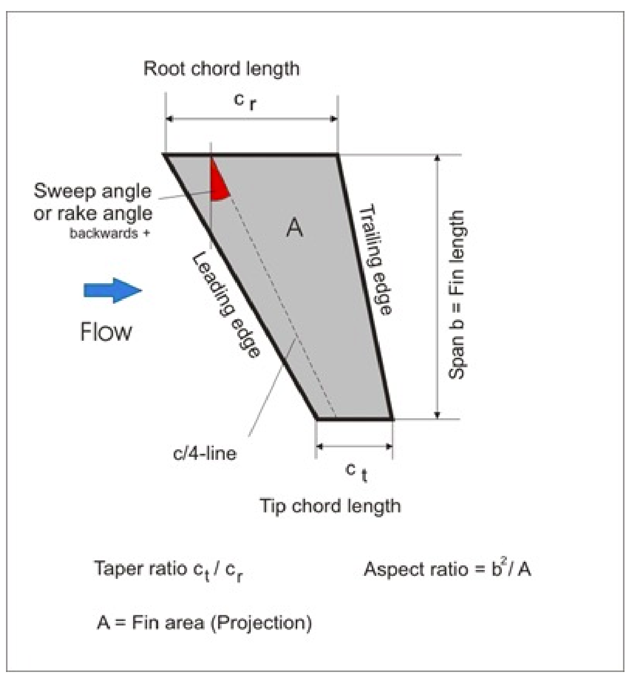
Contains a slot with Flight Computer PCB and Batteries for Power. The avionics bay is attached to bulkhead on the front and rear end and should be easily accessible via an electronics access hatch for debugging and connecting power just before launch

Avionics Bay

Fins

The purpose of fins in rockets is to provide static stability. It moves the centre of pressure below the centre of gravity thereby creating an inherently stable design which provides restorative torque to prevent tilting of flight direction and tries to maintain 0 angle of attack.





Design

The design parameters we have chosen for our rocket

Element	Material	Type	Dimensions	Mass
Nose Cone	PLA	LD-Haack (Von Kármán)	Outer Dia = 75mm Length = 18mm Shoulder = 1mm Thickness = 2mm	66.6g
Body Tube	PVC Pipe	Cylindrical tube	Outer Dia = 75mm Length = 0.95m Thickness = 2mm	606g
Avionics Bay	Electronics, PCB, PLA Mount, Batteries, wires, screws, etc	-	Length 15cm Dia 6cm	75g
Bulkheads	PLA	Annular disc	Dia 71mm Thickness 5mm	24.5g
Motor Mount	PLA	Cylindrical tubes Cluster of 3	Length 10cm Dia 2.9mm Thickness 5mm	140g
Fins	PLA	Trapezoidal set of 4 Airfoil NACA006	Root chord 9cm Tip chord 6cm Height 6cm Sweep angle 36.9	56.9g

Analysis

We carried out component-wise analysis using OpenRocket software

Assumptions (From OpenRocket Tech Doc)

- The angle of attack is very close to zero
- The flow around the body is steady and non-rotational
- The rocket is a rigid body.
- The nose tip is a point
- The fins are flat plates
- The rocket is axially symmetric.

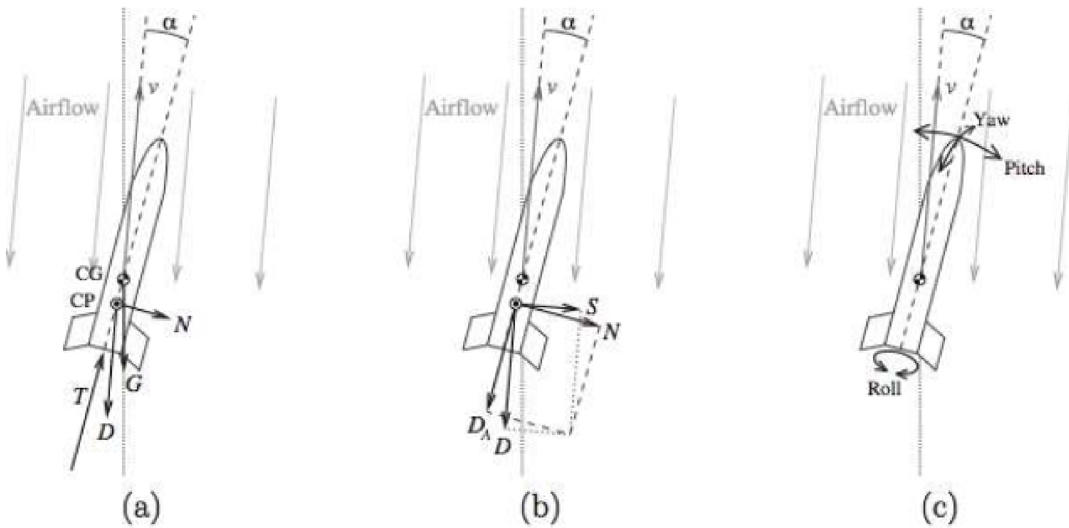
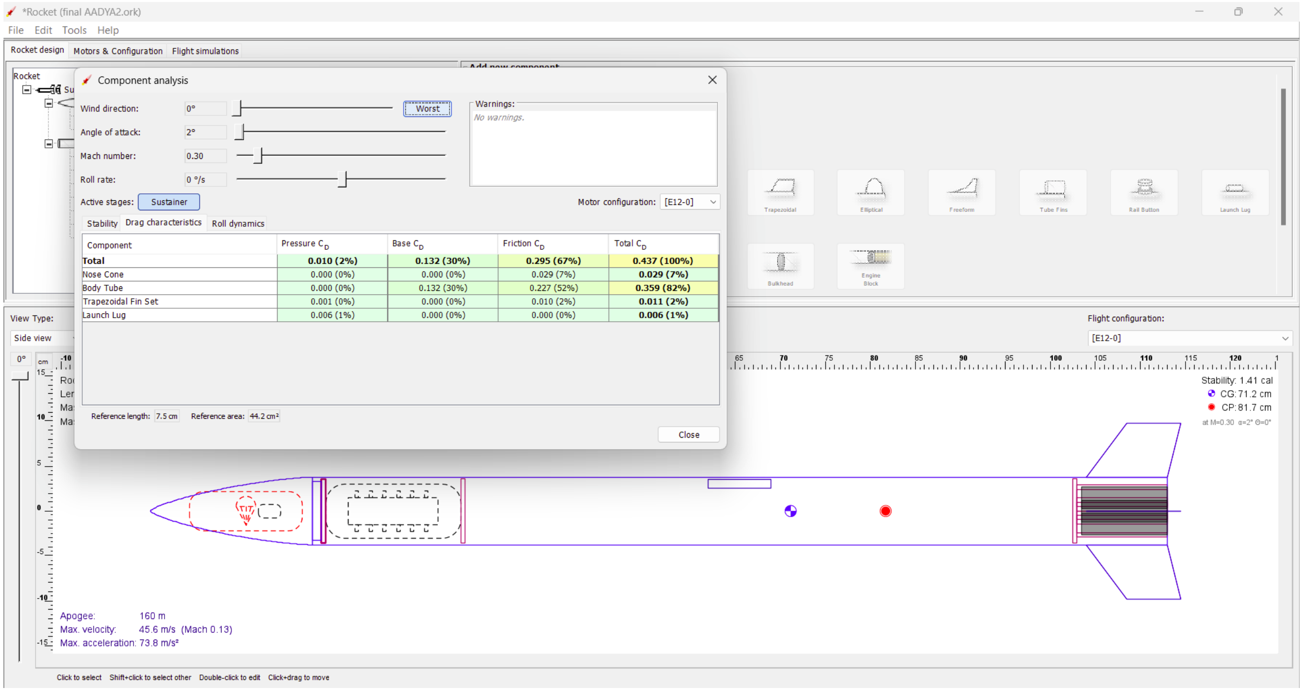


Figure 3.1: (a) Forces acting on a rocket in free flight: gravity G, motor thrust T, drag D and normal force N. (b) Perpendicular component pairs of the total aerodynamical force: normal force N and axial drag D_A; side force S and drag D. (c) The pitch, yaw and roll directions of a model rocket.

Free Body Diagram of Rocket (OpenRocket Technical Documentation)

DRAG CALCULATIONS



Drag Coefficients for each component

Component	Pressure C_D	Base C_D	Friction C_D	Total C_D
Total	**0.010 (2%)**	**0.132 (30%)**	**0.295 (67%)**	**0.437 (100%)**
Nose Cone	0.000 (0%)	0.000 (0%)	0.029 (7%)	**0.029 (7%)**
Body Tube	0.000 (0%)	0.132 (30%)	0.227 (52%)	**0.359 (82%)**
Trapezoidal Fin Set	0.001 (0%)	0.000 (0%)	0.010 (2%)	**0.011 (2%)**
Launch Lug	0.006 (1%)	0.000 (0%)	0.000 (0%)	**0.006 (1%)**

Drag Force on each component was calculated using the following equation

$$C_d = \frac{D}{\frac{1}{2}\rho {v_o}^2 A_{ref}}$$

α: AOA (We have taken as 2 degrees)

A_{ref}: Reference Area

Since we are dealing with aerodynamic forces, the dependence can be characterised by some area. But which area do we choose? If we think of drag as being caused by friction between the air and the body, a logical choice would be the total surface area of the body. If we think of drag as being a resistance to the flow, a more logical choice would be the frontal area of the body that is perpendicular to the flow direction.

NOTE:

For Nose Cone we take the frontal area and for the body tube and fins we use the surface area.

We neglect the launch lug in our analysis as it wont contribute much to the calculations required for the major design decisions

Element	Drag Force
Nose Cone	0.041 N
Body Tube	32.74 N
Trapezoidal Fin Set	0.063 N

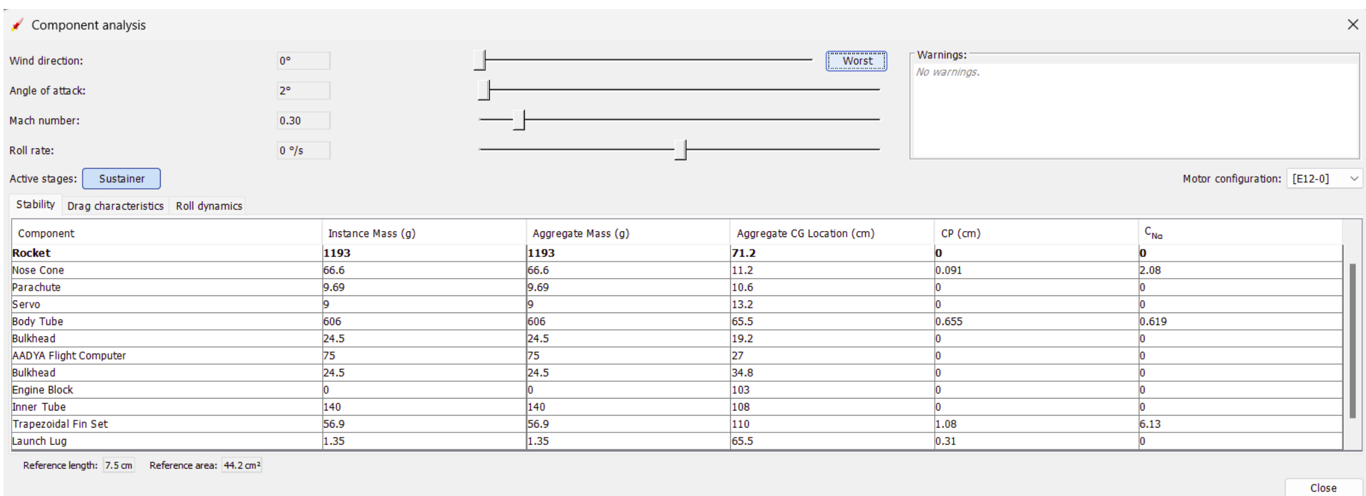
NORMAL FORCE

Normal Force on each component was calculated by the following equations

$$C_n = \frac{N}{\frac{1}{2}\rho {v_o}^2 A_{ref} d}$$

$$C_{n\alpha} = \frac{C_n}{\alpha}$$ From Barrowman's method

d: Reference length which we took as Outer diameter of the body tube



Component	Instance Mass (g)	Aggregate Mass (g)	Aggregate CG Location (cm)	CP (cm)	$C_{N\alpha}$
Rocket	**1193**	**1193**	**71.2**	**0**	**0**
Nose Cone	66.6	66.6	11.2	0.091	2.08
Parachute	9.69	9.69	10.6	0	0
Servo	9	9	13.2	0	0
Body Tube	606	606	65.5	0.655	0.619
Bulkhead	24.5	24.5	19.2	0	0
AADYA Flight Computer	75	75	27	0	0
Bulkhead	24.5	24.5	34.8	0	0
Engine Block	0	0	103	0	0
Inner Tube	140	140	108	0	0
Trapezoidal Fin Set	56.9	56.9	110	1.08	6.13
Launch Lug	1.35	1.35	65.5	0.31	0

Element	$C_{n\alpha}$	Normal Force coefficients	Lift Force
Nose Cone	2.08	0.072	0.046 N
Body Tube	0.619	0.021	0.065 N
Trapezoidal Fin Set	6.13	0.214	2.64 N

One can clearly see that the fins generate the largest normal force on the rocket by a large margin. This is because the fins function is to keep the rocket flying with no angle of attack. The large normal force, created by the fins, imposes a corrective moment on the rocket, forcing it back to an angle of attack of zero.

AXIAL STRESS ANALYSIS

The rocket has three forces acting upon it axially during flight. These forces are drag, thrust and inertial forces. We have calculated drag force. Our rocket thrust force is known because it is a commercially available motor E6-3. According to the data from Estes our motor can produce a maximum of 33N thrust.

Finally, the rocket's structure will experience an inertial load from the acceleration during lift off. According to the model of our rocket, constructed in the Open Rocket software, there will be a maximum acceleration of 73.8m/s^2

Notice that the thrust force is taken to be negative, while the drag and inertial forces are taken to be positive.

$$F_{axial} = -F_{thrust} + D_{nosecone} + D_{bodytube} + D_{fins} + a_{axial}m_x$$

$$\sigma_{axial} = \frac{F_{axial}}{A}$$

Element	Axial Stress
Nose Cone	767559.16 Pa
Body Tube	803748.00 Pa
Bulkhead	212577.40 Pa
Trapezoidal Fin Set	311.27 Pa

σ_{max} of PLA = 40.3MPa

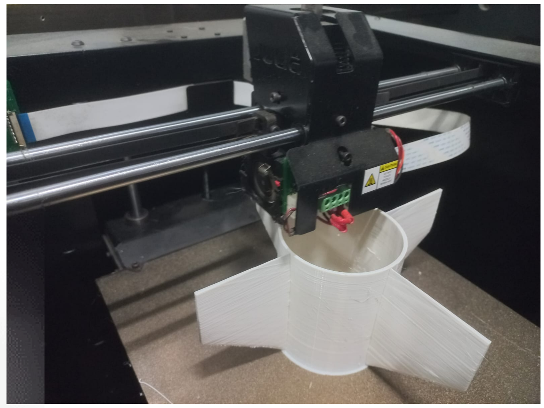
σ_{max} of PVC = 52MPa

In the design process of actual rockets we have to check if the stresses on our components are less than the maximum stress to prevent structural failure. Here all the stresses are well within the limits therefore the materials which we have chosen for the components will not fail.

Fabrication

The nose cone, avionics bay, bulkheads, motor mounts and fins were manufactured by us using 3D printing using PLA filament.

Post-processing involves removal of supports, sanding and epoxy coating for smoother finish and better aerodynamic performance.



Integration

Nose Cone fitted using friction fit so that it can be pushed out by deployment charge for deploying parachutes
Fin roots strengthened using epoxy adhesive
Avionics PCB attached to mount via screws and battery attached by zip ties
Bulkheads screwed to the body tube to fix their location and not allow it to slide inside.

References

OpenRocket Technical Documentation https://openrocket.info/documentation.html
Nose Cone wikipedia https://en.wikipedia.org/wiki/Nose_cone_design
Drag equations https://www.grc.nasa.gov/www/k-12/rocket/drageq.html