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Structural Design and Analysis of High-Powered Model Rockets

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ABSTRACT: Model rockets fall under the category of high-powered small rockets. Usually, a model rocket has a single stage or two stage separation. These high-powered model rockets can be used for educational purposes such as understanding and practically experimenting the concepts of external vehicle forces, rocket stability, aerodynamics, thrusting, and testing purposes, especially for rocket enthusiasts. Model rockets are inexpensive and mostly does not require any legal concerns for its launch. The model rocket designed in this study aimed to achieve an apogee of 1000m or more, with the total length less than 1m and weigh less than 600 grams. The software tool used for this is OpenRocket. The material for nose cone, the payload tube, transition, recovery or parachute tube, booster tube and fins were selected based on the density and weight constrains. The modelled rocket can carry a payload of 50 grams and a recovery system with canopy and shroud lines. This developed prototype rocket is powered with a solid motor which can support its ignition and thrusting. Finally, the study shows the apogee achieved, vertical velocity and the maximum acceleration achieved for the high-powered model rocket.

Keywords: High powered rocket design, model rocket, apogee, model rocket stability, solid propellent **1.**

I. INTRODUCTION

The parts of the model rocket include nose cone, payload tube, parachute tube, recovery wadding, booster tube or an engine mount and fins.[1] The nose cone directs the flow of air smoothly around the rocket, the shape and configurations of the nose cone varies from high powered rockets to commercial space launch vehicles. The design of shape and type of nose cone affects the percentage of drag and depends on the Mach number required for the flight.[2] The payload tube is present to allocate enough space for the electronics, cameras and essential avionics components required for the rocket. The body tube is the basic airframe of the rocket to which all other parts are attached. The recovery system consists of a parachute or streamer which will safely return the model. The recovery wadding prevents the hot gasses from damaging the recovery system.[3] The fins provide the dynamic stability for the rocket. The type of fins used varies for each application, these are present in the rear end of the rocket to support the flight by assisting with stability control and preventing the rocket to wobble. Finally, the engine mount securely holds the engine.[4]

The rocket is launched in a vertical launch guide using a static test pad, this ensures that the rocket is in an upright position until it has sufficient velocity for the fins to aerodynamically stabilize the flight. After clearing the launch guide the rocket attains free powered flight.[5] The motor accelerates the rocket in a vertical and aerodynamically stabilized way. When the rocket is nearing the apogee, the recovery system is released with the upward firing of a pyrotechnical ejection which pressurizes the model rocket and opens the recovery device.[6]

The objective of this work is to design a model rocket which can reach an apogee greater than 1000m and weight less than 600 grams. The required model was designed using OpenRocket software tools and the apogee, vertical velocity and maximum acceleration of the model rocket were simulated and plotted with the assistance of this software.

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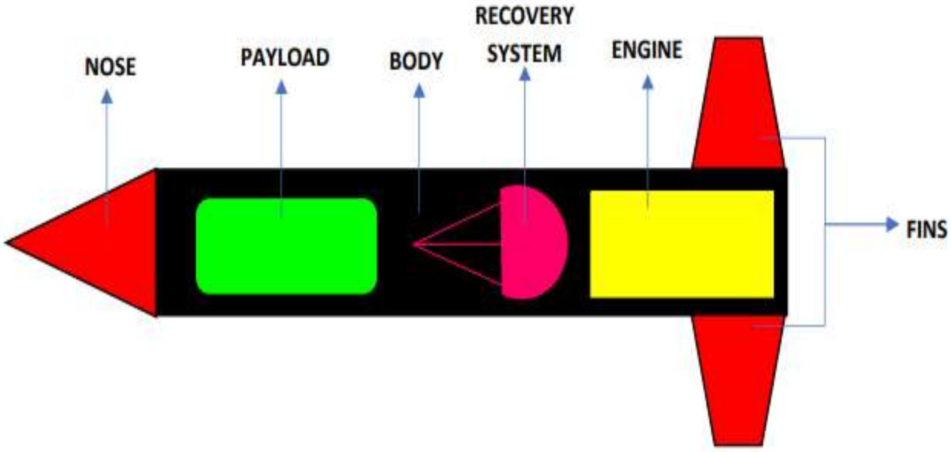

Fig 1: Graphical Representation of Structure of the Model Rockets

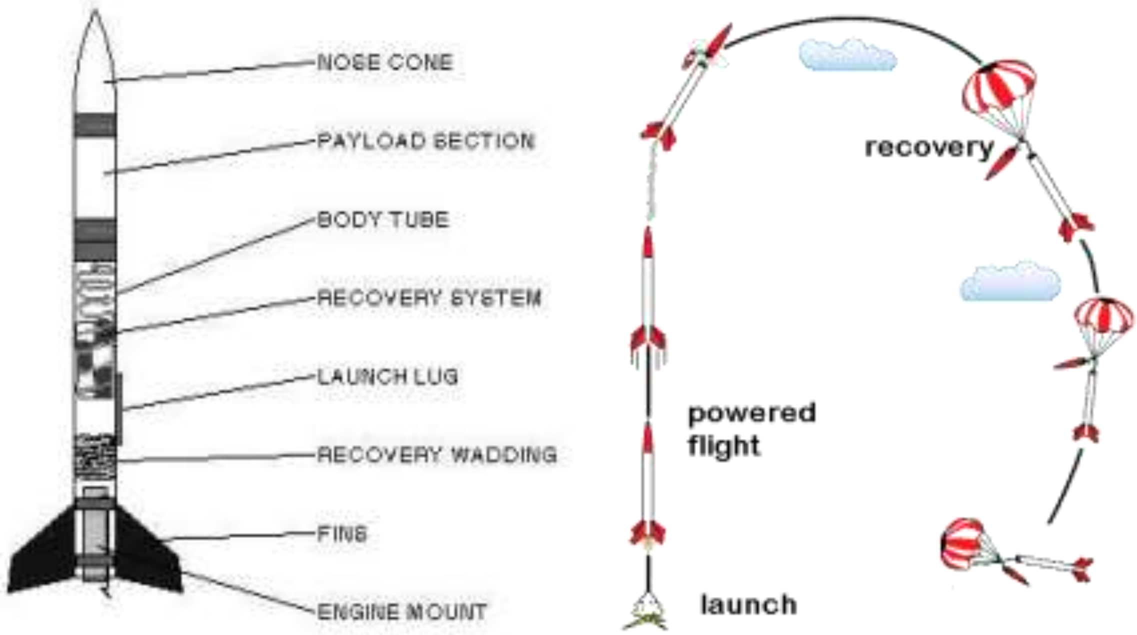

Fig 2: Parts of Model Rocket and the Illustration of parachute ejection system [7]

II. EXPERIMENTAL SETUP

2.1 Rocket Stability

The two main parameters that influence a rocket as centre of gravity (CG) and centre of pressure. The centre of gravity (CG) for a rocket can be found by balancing the rocket using your hands similar to balancing a pencil. It is at this point, the amount of mass on both sides are equal. The mass distribution of the rocket is uniform, and the centre of gravity (CG) is exactly in the middle. [8]

On the other hand, finding the centre of pressure (CP) of the rocket is difficult to comprehend. It is the point along the rocket z axis with the same amount of surface area on both sides. Generally, it is difficult
to extract this point by simple methods and usually calculated experimentally in a wind tunnel or with the help of numerical equations.

The position of the centre of gravity (CG) and centre of pressure (CP) plays a critical role with respect to calculating the stability. The rotation of the rocket takes place around the centre of gravity (CG) during the flight and the gravity acts on that singular point. Whereas forces such as drag and pressure act on the centre of pressure (CP). These two factors decisively judge the stability of rocket.[9]

During the launch, the centre of gravity (CG) is dependent on the burn time. The centre of

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gravity (CG) will move upwards to the rocket due to the fuel and oxidizer placed I the rear end of the rocket.[10] The centre of pressure (CP) is dependent on the velocity of the rocket in the medium through which it flies, in this case air. The OpenRocket software considers the medium, centre of gravity (CG) and centre of pressure (CP).

The stability of the rocket in terms of centre of gravity (CG) and centre of pressure (CP) can also be states. If the centre of gravity (CG) is in front of the centre of pressure (CP), the rocket is stable. The more the centre of gravity (CG) is away from the centre of pressure (CP), the more stable the rocket is.[11]

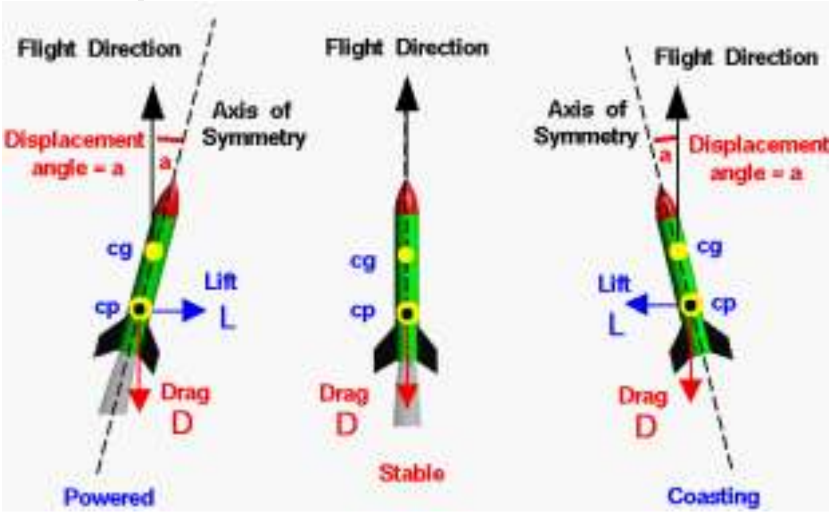

Fig 3: Illustration of the direction of rocket along its flightpath [12]

The stability margin (SM) determines the stability of the rocket. Stability margin (SM) is where the distance between the centre of gravity and centre of pressure is divided by the diameter ‘d’ of the body of the rocket.[13] The general rule while designing a model rocket is that the stability margin should be greater than 1 but less than 2 can be simplified as (1 <SM< 2). The stability margin (SM) is given by the formula:

$$SM = \frac{CG - CP}{d}$$

Where:

CG – Centre of Gravity

CP – Centre of Pressure

d – Diameter of Rocket Body Tube

Stabilization of the rocket can be done in two ways: active and passive stabilization. In active stabilization, the rocket engine is used to control the attitude of the rocket. This method is quite expensive and complex. It is usually used in larger launch vehicles.

There are two ways to stabilize rockets: active and passive. Active stabilization is using rocket engines (like gimballing the main thrusters or using smaller engines called Vernier thrusters) to control the attitude of the rocket. Active controlling is expensive and complex, but on large rockets it is necessary to use it as active controls are movable. Passive controls on the contrary are fixed devices such as the avionics in the rocket which are used to keep the rocket stabilized.

2.2 Forces on Rocket

Forces such as weight, thrust, drag, and lift act on the model rocket. These forces change dramatically with respect to magnitude and direction as the rocket progresses in flight. The rocket is mainly subjected to lift, drag, weight and thrust during the powered flight.[14] For a rocket, the direction of flight is vertical, the drag and weight forces act almost in the same direction. Finally, the rocket engine must exert a force in order to overcome the weight and drag forces. The drag and thrust is along the direction of the flight.

Due to weather cocking, the path of the flight will be inclined to a local vertical and horizontal. The forces can be split into vertical and horizontal components using the angle of inclination (θ) as shown in the figure and the net horizontal force and vertical forces are derived.

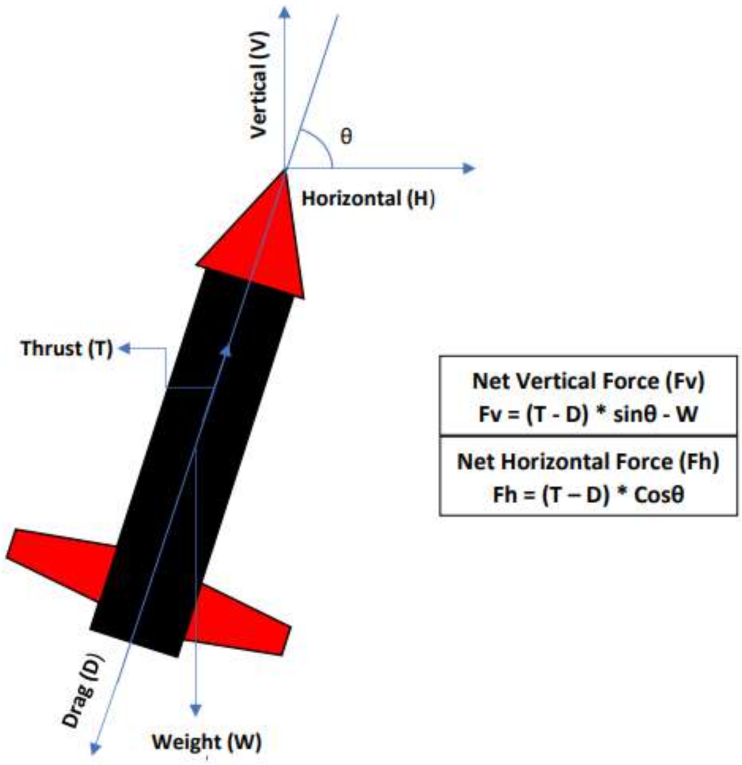

Fig 4: Flight Path for Powered Rockets

The net horizontal force (Fh) is given by the substraction of the Thrust (T) and Drag (D) and multiplying with the cosine of the inclination angle θ as these forces act on the opposite direction:

Fh = [T - D] * cos b.

Similarly the net vertical force (Fv) is given by substracting Drag (D) from Thrust (T) and multiplying with sine of the inclination angle θ minus the weight:

Fv = [T - D] * sin b - W

For smaller rockets such as high-powered model rockets are launched, the wind-blown acts on the centre of pressure and make the rocket to tilt towards the direction of the wind during its thrust phase and drift slightly during the non-thrusting phase. This effect becomes negligible for larger rockets and diminished with the increase in altitude due to the decrease in the air density.

2.3 Weather Cocking

The influence of the wind making the rocket turn is known as weather cocking. This term "weather cocking" was derived from the word "weather-vane". The velocity of the rocket increases just after the launch along with the increase in the aerodynamic forces from the nose cone to the rear end. In case of no wind, the path of the rocket would be vertical, and the relative air velocity would also be vertical opposite to the flight direction of the model rocket. Wind acts as an additional component by producing an effective flow direction by making an angle to the flight path. The flight path depends on the relative magnitude of the wind as well as the velocity of the rocket. The lift forces make the rocket spin about the centre of gravity (CG) and produce a new flight path with the wind. This aligns the rocket with the direction of flow of wind, hence there is no longer any lift force.

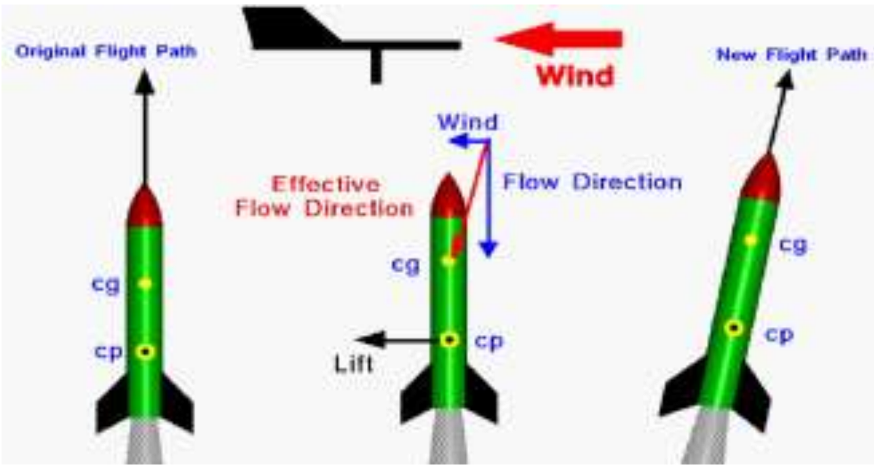

Fig 5: Represents the inclination due to weather cocking [15]

The angle of tilt in due to weather cocking can be calculated as tan θ, where θ is the angle of inclination with respect to the horizontal direction. The anlge of tilt is given as:

Tan θ = V/W

Where:

V = Velocity of Rocket (m/s^2)

W = Weight (g)

III. METHODS AND MATERIALS

3.1 Nose Cone

The nose cone shape selected for the design is "Haack". This is specifically designed for minimizing the drag and produces a value of 0.333 LV-Haack nose cone for a fixed length and volume. The length of the nose cone is 17cm with a base diameter of 5cm. The thickness of the nose cone is 0.5cm or 5mm. The material selected for the nose cone is Blue Tube which has a density of $1.3g/cm^3$. The mass of the nose with an estimated regular paint for the component as 60µm is 96.5g.

3.2 Payload Tube

The payload tube of 15cm in length, 5cm as outer diameter and 4 cm as inner diameter is designed. The wall thickness is constant throughout as 0.5cm. The material selected for the payload is Balsa wood with a density of $0.17g/cm^3$ with regular paint for component finishing as 60µm. The weight for this body tube configuration is 18g.

3.3 Transition

There are a variety of shapes available for transition tube such as conical, ogive, power series, ellipsoidal, parabolic series and haack series. The shape of the transition tube selected is conical. Conical shape for preferred due to better straightness. The transition length of 6cm, fore diameter (larger diameter) as 5cm and the after diameter (narrower diameter) as 3.4cm. The wall thickness considered for this transition was 0.5cm. The material selected was Balsa wood with density of $0.17g/cm^3$. The weight of the transition tube was 5.97g.

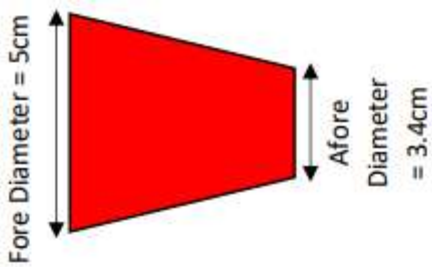

Fig 6: Graphical illustration of transition tube

3.4 Parachute Tube

The parachute tube consists of a recovery system for safer deployment of the payload. The parachute tube was designed to have a length of 13 cm, outer diameter of 3.4cm and inner diameter of 2.4cm. The thickness of the wall was 0.5cm. The material chosen for this tube was balsa wood with density of $0.17g/cm^3$. The mass the parachute tube was 10.1g.

3.5 Booster Tube

The booster tube consists of the rocket motor for thrusting. The booster tube was designed to have a length of 21 cm, outer diameter of 3.4cm and inner diameter of 2.4cm. The thickness of the wall was 0.5cm. The material chosen for this tube was balsa wood with density of 0.17g/cm^3. The mass the parachute tube was 16.3g.

3.6 Fins

Four set of trapezoidal fins were deployed for better stability. The fins have a sweep length of 2.5cm, root chord of 5cm and height of 3cm. The sweep angle is 38.9˚. The thickness of each fin was 0.2cm and mass for each of the four fins are 2.02g. The material used for designing the fin is balsa with density of 0.17g/cm^3.

3.7 Motor

There are different classes of motors. High power motors which are classified as "H" or above or have an average thrust over 80 N/s. The motor selected for this study is “AeroTech H195NT”. This is a single use motor. Considering the factors of safety, reliability, and readily available when compared to reloadable motors. The properties of used motor AeroTech H195NT motor is given in the following table.

Table 1: Properties of AeroTech H195NT

Properties	**Values**
Total Impulse	237Ns
Average Thrust	205N
Maximum Thrust	257N
Burn Time	1.16s
Launch Mass	197g
Empty Mass	82g
Motor Length	203mm
Motor Diameter	29mm

3.8 Payload

The payload assumed for this study was 100g with a length of 13cm and diameter of 3.5cm. The density for the payload was estimates as 0.8g/cm^3. The position of the payload was fixed respective to the tope component that is the nose cone.

3.9 Recovery tube

The diameter of the canopy was 80cm, and material selected was Ripstop nylon with a density of 67g/m^3. The packed length was 3cm with packed diameter as 10cm. The number of shroud lines selected for the recovery system was 6 with the length of 30cm and the material elastic chord of 1.8g/m^3.

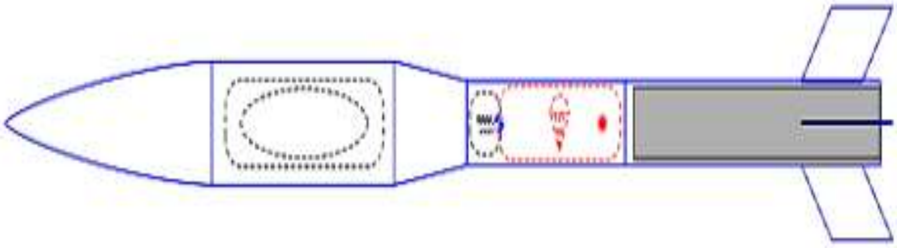

Fig 7: Side View of the Rocket Design in OpenRocket

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The mass distribution for each component, the length of each part in the model rocket, the density of the materials used and the preferred shape for the components is listed in the figure 8.

Nose cone	Blue tube (1.3 g/cm³)	Haack series	Len: 17 cm	Mass: 96.5 g
Payload Tube	Balsa (0.17 g/cm³)	Dia_{in} 4 cm Dia_{out} 5 cm	Len: 15 cm	Mass: 18 g
Payload Distribution		Dia_{out} 3.5 cm		Mass: 100 g
Transition	Balsa (0.17 g/cm³)	Fore Dia: 5 cm Aft Dia: 3.4 cm	Len: 6 cm	Mass: 5.97 g
Parachute	Balsa (0.17 g/cm³)	Dia_{in} 2.4 cm Dia_{out} 3.4 cm	Len: 13 cm	Mass: 10.1 g
Parachute	Ripstop nylon (67 g/m²)	Dia_{out} 80 cm	Len: 10 cm	Mass: 36.9 g
Shroud Lines	Elastic cord (round 2 mm, 1/16 in) (1.8 g/m)	Lines: 6	Len: 30 cm	
Shock cord	Elastic cord (round 2 mm, 1/16 in) (1.8 g/m)		Len: 40 cm	Mass: 0.72 g
Booster Tube	Balsa (0.17 g/cm³)	Dia_{in} 2.4 cm Dia_{out} 3.4 cm	Len: 21 cm	Mass: 16.3 g
Trapezoidal fin set (4)	Balsa (0.17 g/cm³)	Thick: 0.2 cm		Mass: 2.02 g

Fig 8: Mass Distribution for each component

IV. RESULTS

With respect to the given dimensions, motor specifications and configurations it was summed that the total length of the rocket was 73cm and the maximum diameter was 5cm. The total mass of the rocket with the motor loaded was 484g.

The design and configurations of the rocket was satisfied by the value of stability margin (SM) falling at 1.7 which is above 1 and below 2. The centre of gravity (CG) was located at 40.6cm from the top and the centre of pressure (CP) was located at 49.1cm from the top.

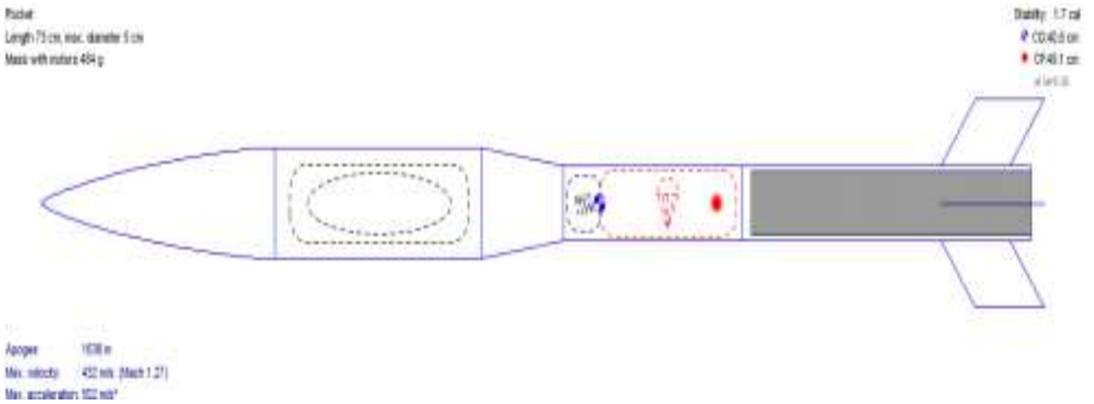

Fig 9: Final design of the high-powered model rocket

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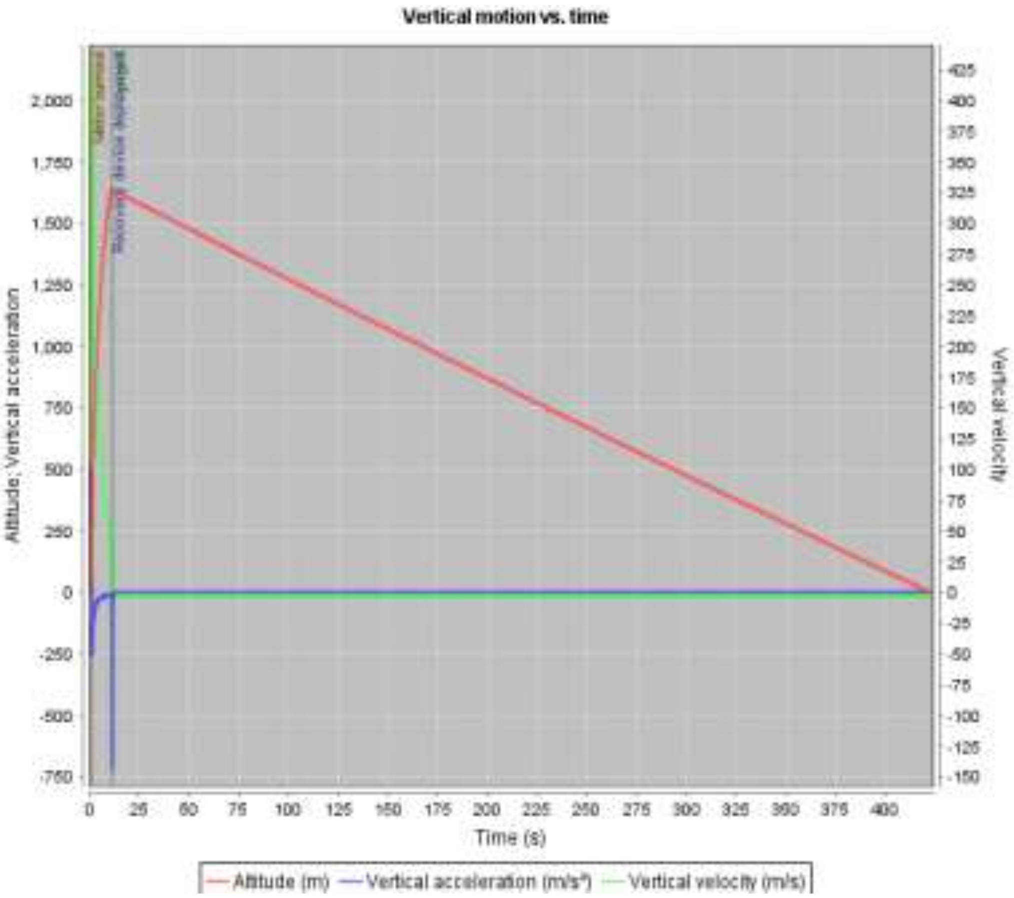

Fig 10: Model Rocket Simulation Graph

With the simulation results it was confirmed that the modelled rocket could reach an apogee of 1636m, with vertical velocity 432m/s of and maximum acceleration as 502m/s^2. The time taken to reach the apogee was 11.7 seconds. The Mach number of this simulation was derived to be 1.27 which states clearly that the flight path is supersonic as Mach>1. The velocity of deployment was 35.2m/s, with flight time of 423 seconds which is nearly equal to 7 minutes. The ground hit velocity obtained was 4.01m/s. The graph illustrates the simulation of the vertical velocity (m/s) and vertical acceleration(m/s^2) with respect to the time in seconds.

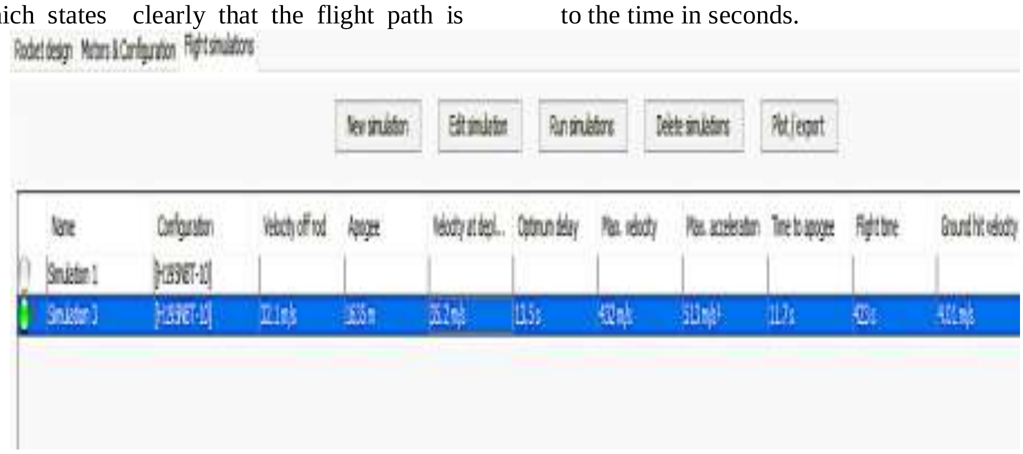

Fig 11: Results of the simulation of the model rocket

The following figure 12 and figure 13 shows the unfinished and finished 3-dimensional view of the modelled rocket. The red coloured point represents the centre of pressure (CP) and the

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blue coloured point represents the centre of gravity (CG)

Fig 12: Unfinished 3-dimensional view of the model rocket

Fig 13: Finished 3-dimensional view of the model Rocket

V. CONCLUSION

This study concludes that the designed high-power model rocket using OpenRocket software tool is capable of having an apogee of 1636m, with vertical velocity 432m/s of and maximum acceleration as 502m/s^2. The overall mass of the rocket is 484g and the length of the rocket is 73cm. Further enhancement of this study could be done by implementing the concepts of design in real time with the assistance of the avionics support system and detailed design of the recovery system. By performing this experiment, students and rocket enthusiast can understand the theoretical learning and experiment the concepts learnt in practical work. Moreover, performing this experiment will not be dangerous due to the rocket motor selected and the limited apogee of 1636m which does not require any special permissions from the government officials.

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