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Comparative study on designs of air propelled rocket for achieving higher altitude

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Abstract- Model rockets are essentially unguided models of a rocket that are a paramount mode to learn and simulate the concept of physics and all the other parameters that can be applied on a guided missile and guided rocket. There are many model rockets available that use different propellants like water, motor engines, and diverse fuels. Implementing these propellants in a model rocket is difficult and sometimes risky. This paper delivers a solution to the problem by proposing a model rocket where the air is used as a propellant. The paper provides detail about designing a rocket and study of various parameters that effect to a design of rockets, like mass, centre of mass, centre of pressure, forces and stability margin. The objective of this paper is to make model rocketry safe, design a stable rocket, design rocket using mathematical techniques and also using open-source software. This paper also provides some original designs that can achieve maximum height with low input force.

Keyword- Model rockets, designing, stability, high altitude, centre of mass, centre of pressure

1 INTRODUCTION

The model rocketry is a sport that involves designing, constructing and launching self-made rockets. Model rockets vary greatly in size, shape, weight and construction from detailed scale models of professional rockets to lightweight and highly finished competition models. The sport is relatively popular and is often cited as a source of inspiration for children to become engineers and scientists.

The hobby started as amateur rocketry in the 1950's when hobbyists wanted to experiment their skill with building rockets. Designing, building and launching self-made fuel rockets was, however, extremely dangerous, and the American Rocket Society (now the American Institute of Aeronautics and Astronautics, AIAA) has estimated that about one in seven amateur rocketeers during the time were injured in their hobby. For this experimenting with model rockets using different propellant is not safe and economical.

This paper explains how this is overcome. Paper model rockets are the best which can be used to learn the concept of real rocket safely. So this document discusses how to design a paper rocket and also stability of rockets that would lead it to achieve maximum height. Additionally we propose some examples and designs.

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2 RELATED WORK

STABILITY OF ROCKET

In designing any type of rocket stability places an important role. The concept of centre of pressure and centre of gravity plays and important role for designing a stable rocket. Centre of mass or centre of gravity (CG) can be easily calculated experimentally whereas centre of pressure (CP) is slightly difficult to determine analytically. In 1966 James and Judith Barrowman developed an analytical method for determining the CP of a slender-bodied rocket at subsonic speeds and presented their results as a research and development project at the 8th National Association of Rocketry Annual Meeting (NARAM-8), and later as a part of James Barrowman's Master's thesis. This method has become known as the Barrowman method of determining the CP of a rocket.

If the rocket is stable then in will be capable enough to achieve its objective. After rocket launched during the lift off the rocket experiences various forces that can change the orientation of the rocket. Like a small wind force may cause rocket tilt slightly from its current orientation. When such thing happens the rockets Orientation i.e. rockets centreline is no longer parallel to the direction of velocity. At this point

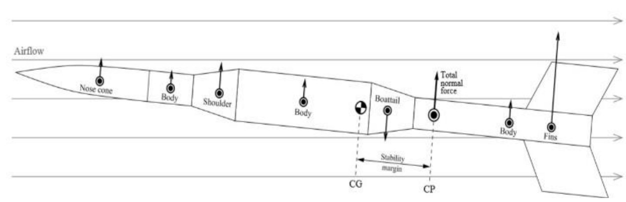


Figure 1: Forces produced on the rocket components

the rocket is flying at an angle α, this angle α is known as angle of attack which is nothing but the angle between centreline of the rocket and the direction of velocity vector.

When a stable rocket moves at the angle of attack the rocket fins corrects the movement. Due to forces produced in perpendicular direction the fins produces corrective movement. Every component of rocket experiences a normal force originating at the centre of pressure of that component. These forces can summed up and applied at such a point where it created the same impact. The resulting force will have magnitude of sum of magnitude of all the forces. The point at which the resulting force act is known as centre of pressure (CP) of the rocket. Figure 1 shows the various forces acting on a rocket body and the resulting force acting on the centre of pressure point.

The point where the mass of entire rocket body is concentrated is known as centre of mass or centre of gravity (CG) of the body. To calculate stability or stability margin CG and CP are very important. It can be seen from the figure that the movement produce to correct the rocket flight only if CP is located after CG. In this case a rocket hold a stability condition and these types of rockets are known as statically stable rockets.

Stability margin is the distance between the CP and CG, measured in calibres.

Above we discuss the forces that are generated on particular components of rocket also known as normal force but from where this forces are generated? There are three basic forces that acts on a model rocket: Thrust force, gravitational forces and aerodynamic forces. These forces are also called external force which is been acted during the flight of rocket. The model rocket designs discussed, tested and analysed in this paper is an air propelled rocket where the propellant will be air and the thrust will be created due to the sudden air pressure created in the cylindrical part of the rocket. The air pressure is created when you apply enough force on the stomp pad of the rocket launcher. The thrust created will be directly proportional to the force applied on the stomp pad.

CENTRE OF MASS OR CENTER OF GRAVITY

Centre of gravity is that point of rocket where it balances i.e. there is as much weight distributed ahead of rocket's CG as there is behind. Simply we can say CG is the point where entire body mass is concentrated. Finding CG of a model rocket is simple, it involves balancing a fully constructed model rocket over a point. Mark the point where the rocket is levelled, the point marked is the CG of the rocket.

This method of finding CG is very simple and applicable for model rockets but in the case of real rocket it is not possible to balance a rocket over a string. Another method of finding the location of CG is analytical method where centroid of every component is calculated and then following equation is used to compute the CG.

Calculating Centre of gravity of rocket

$$\bar{x} = \frac{\sum Ax}{\sum A}$$

A = Area of each section

x = Distance from the centroid of each section to the base.

$\bar{x}$ = Center of mass of rocket.

CENTRE OF PRESSURE

Centre of pressure is similar to centre of mass except here forces are involved to define the CP point on a rocket. CP is a point on rocket where, air pressure forces distributed ahead this point and behind are equal. CP is point on a rocket where all the forces acting on a rocket are concentrated or we can say it's a point where we can apply summation of all the forces acting on rocket.

Before calculating the centre of pressure of a model rocket we have made some assumptions for this report which are as follows:

1. The speed of the rocket is much less than the speed of sound.
2. The rocket is thin compared to its length.
3. The nose of the rocket comes smoothly to a point.
4. The rocket is axially symmetric.
5. The fins are thin flat plates.
6. Input force was kept constant while testing the rockets.

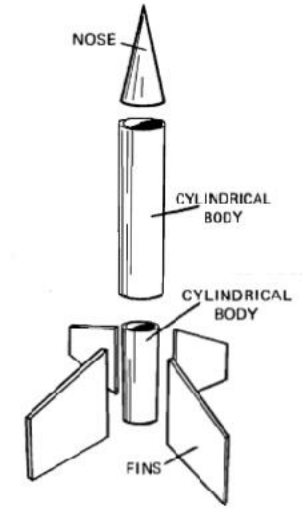


Figure 2: Rocket body parts

CENTRE OF PRESSURE BY BARROWMAN EQUATION.

The Barrowman equation allows you to determine the stability of rockets by computing the centre of pressure. To find the stability of rocket we need both the centre of gravity and centre of pressure. Using Barrowman equation we can find CP. To find out the centre of pressure we need to analyse each component separately. Generally a model rocket has five sections i.e. Nose, transition section, cylindrical body, boat tail and fins. The rocket designed in this report do not have all of these sections. We have only three sections i.e. Nose, Cylindrical body and fins. So we need to analyse these three section individually. You can see the three body parts in the diagram on right.

Notation description

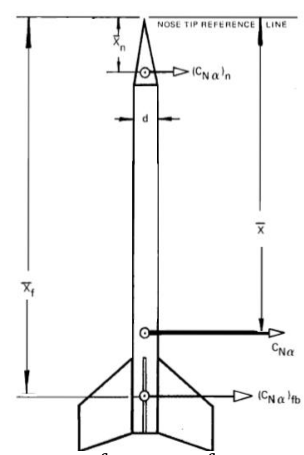


Figure 3: Centre of pressure and Normal force position

$\bar{X}n =$ poistion of centre of pressure from top of nose cone.

$(C_{N\alpha})_n$ = Normal force on nose cone.

d = Maximum diameter of rocket.

$\bar{X}$ = Centre of pressure of entire rocket.

$\overline{Xf}$ = Centre of pressure of *fins*.

$(C_{N\alpha})_{fb}$ = Normal force on fins.

Calculating the centre of pressure of rocket using barrowman equation.

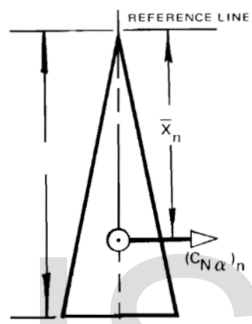
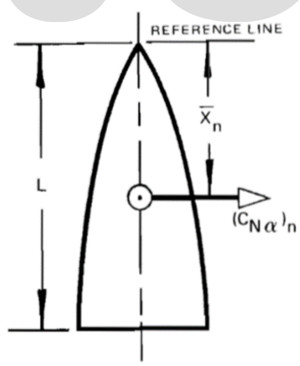
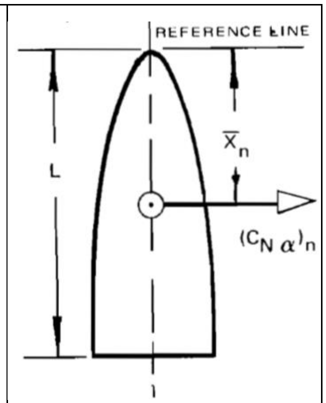
To calculate CP of any rocket body we need to analyse and find CP of every part of rocket body. Like if we have nose cone, body and fins then we need to calculate CP and normal force acting on it and then combine it to get the CP of entire body.

Nose cone

Generally, the normal force on nose is given as $(C_{N\alpha})_n$ which is identical for all the shapes of nose which is conical nose, Ogive shape, and parabolic shape.

$$(C_{N\alpha})_n = 2$$

On the other hand the position of centre of pressure of nose changes with change in shape, which is as follows

Sr.no	Shape name of nose	Position of CP	Shape
1.	Conical nose	$\bar{X}n = \frac{2}{3}L$	
2.	Ogive nose	$\bar{X}n = 0.466\,L$	
3.	Parabolic Nose	$\bar{X}n = \frac{1}{2}L$	

Where, L= Length of nose cone; reference line is the point from where the distance is measured.

Cylindrical body

The next thing that we require is to find the centre of pressure f next component which is the cylindrical body in our case. AS we have considered the angle of attack less than 10 degrees then the normal force on the cylindrical body is negligible which can be illustrated from the graph on the right. The graph shows the relationship between the normal force acting on the body and the angle of attack. As we considered angle of attack less than 10 degrees then the value of normal force tends to be zero or negligible.

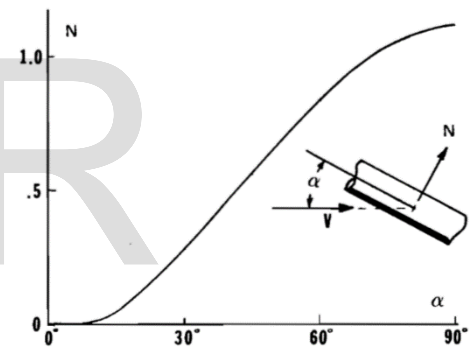


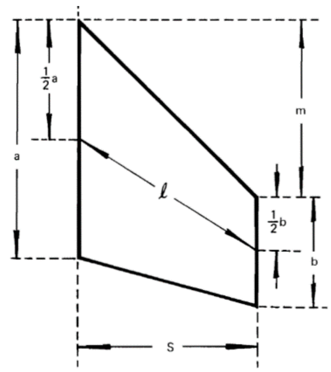
Figure 4: Relationship between normal force on body and angle of attack.

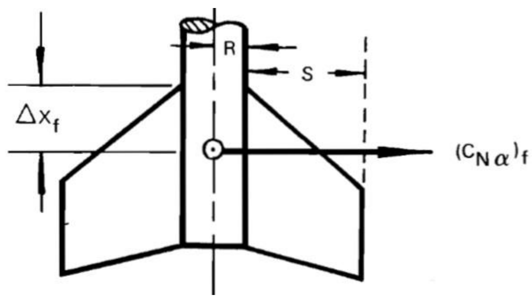
So we do not need to calculate the normal force on the body as it would be zero for angle of attack less than 10 degrees

Fins

The next and most important role that play its importance in stability of a rocket are fins, and in this report we intended to design a stable rocket by alteration in the fins of rocket.

Notational description





a = Fin root chord

b = Fin tip chord

S = Fin Semi span

l = Length of fin mid-chord line

m = Distance between fin root leading edge nd fin tip leading edge parallel to body

ΔX_f = Poistion of CP of fins with body

$(C_{N\alpha})_f$ = Normal force on fins

$\overline{Xf}$ = Centre of pressure of $fins$.

The figure above shows a generalize fin shape. In this segement we need to find the value of $\overline{Xf}$ which is the CP position of the fins and also we need to find the Normal force on the fins and understand the concept of Fin interference factor for stability of entire rocket body.

The centre of fins does not depends upon number of fins. It can be reflected from the following equation, where position of CP of fins is given as

$$\overline{Xf} = \text{Xf} + \Delta\text{Xf}$$

$$\overline{Xf} = \text{Xf} + \frac{m(a + 2b)}{3(a + b)} + \frac{1}{6}\left(a + b - \frac{ab}{a + b}\right)$$

Where Xf = distance between nose tip to front edge of the fin root.

The normal force acting on the rocket fin is given as

$$(\text{CN}\alpha)\text{f} = \frac{4n\,(\frac{S}{d})^2}{1 + \sqrt{1 + (\frac{2l}{a + b})^2}}$$

Where n = numberof fins , n can only be 3, 4 or 6. If the rocket has any other fins, these equations cannot be used.

Fin interferance factor:

The air flow over the fins is influenced somewhat by theair flow over the body section to which the fins are attached . To account for this the fin force for either 3 or 4 finsis multiplied by an interference factor,

$$K_{fb} = 1 + \frac{R}{S+R} \quad \text{(for n = 3 or 4)}$$

Where,

R = radius of body between the fins

S = Fin Span

K_{fb} = fin interference factor of fins in presence of body

The total normal force on the tailin presence of body is given by

$$(C_{N\alpha})_{fb} = K_{fb}\,(C_{N\alpha})_f$$

The centre of pressure of entire rocket body is given by the formula

$$\bar{X} = \frac{((\text{CN}\alpha)\text{n}\bar{X}n + (\text{CN}\alpha)\text{fb}\overline{Xf})}{\text{CN}\alpha}$$

Where,

$C_{N\alpha}$ is the total normal force, which is sum of all the normal force acting on individual part of rocket and given as

$$C_{N\alpha} = (C_{N\alpha})_n + (C_{N\alpha})_{fb}$$

Now we have CP and CG of the rocket. To find whether a rocket is stable we need to calculate the static margin of rocket. If experimental CG is less than calculated CG then the rocket is stable.

3 METHOD

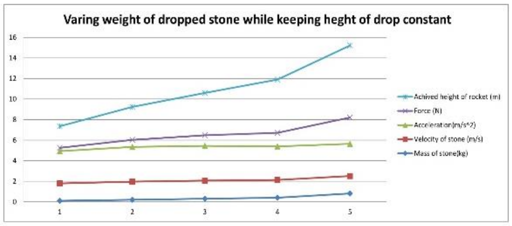
Since this paper contains work on air-propelled rockets, before working on the design of rocket input force need to be taken into account and kept constant. To achieve this weight was dropped from height and iteration in mass and distance was done, simultaneously maximum height achieved during the flight was calculated. (The rocket design used for this observation was taken from Natskies observatory). The result of this is shown below, in first case different object of different mass was dropped from a fixed height and the maximum height of flight was calculated.

In the second case, the weight which resulted in the maximum height of flight was chosen and the height of drop was altered. From this study, we found that 4 kg block when dropped from 4 feet gives a maximum height of 25.59 feet.

Varing weight of dropped stone while keeping heght of drop constant

Height of drop = 3 feets or 0.9144 m

Sr. no	Weight of stone(kg)	Mass of stone(kg)	Velocity of stone (m/s)	Acceleration(m/s^2)	Force (N)	Achived height of rocket (m)
1	1	0.102	1.694	3.1358	0.3198	2.103
2	2	0.204	1.7584	3.3815	0.6898	3.2004
3	3	0.3061	1.7584	3.3815	1.0351	4.114
4	4	0.4081	1.7253	3.2552	1.3286	5.181
5	8	0.8163	1.6934	3.1359	2.5599	7.01



Result 1

Varing height of dropped stone while keeping weight of stone constant

Weight of stone dropped = 4Kg   Mass of stone dropped = 0.4081 Kg

Sr. no	Height of Drop(m)	Velocity of stone (m/s)	Acceleration(m/s^2)	Force (N)	Achived height of rocket (m)
1	0.3048	0.7434	1.81	0.7386	2.98
2	0.6096	1.02	1.717	0.7007	3.474
3	0.9144	1.2356	1.6697	0.6814	5.334
4	1.2192	1.3109	1.4095	0.5752	7.802

Result 2

Result 1 shows the velocity, force, and maximum height achieved by the model rocket when the weight of dropped stone was varied. From result 1 we selected 4 kg block as it was from one of the highest achieved height. Result 2 show the variation in height of dropping the stone. From both the result we conclude that to keep force constant we would drop a 4 keg block/stone from 4 feet height resulting in a force of 0.575N.

Once input force was kept constant we started iteration in rockets design, in which first trials were taken in where the number of fins was varied and stability and maximum height was calculated. Following are the result for the trials.

Sr.no	Dimensions	Three fins	Four fins
1.	Length of nose	3.7”	3.7”
2.	Number of fins	3	4
3.	Fin Semi span	1.41”	1.41”
4.	Length of fin mid-chord line	2.95”	2.95”
5.	Fin root chord	2.64”	2.64”
6.	Fin tip chord	0”	0”
7.	Diameter of rocket body	0.78”	0.78”
8.	Distance between nose tip to front edge of the fin root.	8.6”	8.6”
9.	Type of fins	Triangular	Triangular
10.	**CP distance from top of nose**	**8.981”**	**9.192”**
11.	**CG distance from top of nose**	**8.201”**	**8.412”**
12.	**Maximum height during the flight**	**15.68 feet**	**20.72 feet**

Sr.no	Dimensions	Three fins	Four fins
1.	Length of nose	2.67”	2.67”
2.	Number of fins	3	4
3.	Fin Semi span	1.56”	1.56”
4.	Length of fin mid-chord line	1.71”	1.71”
5.	Fin root chord	1.56”	1.56”
6.	Fin tip chord	0.78”	0.78”
7.	Diameter of rocket body	0.78”	0.78”
8.	Distance between nose tip to front edge of the fin root.	11”	11”
9.	Type of fins	Trapezoidal	Trapezoidal
10.	**CP distance from top of nose**	**10.85”**	**11.85”**
11.	**CG distance from top of nose**	**10.07”**	**10.28”**
12.	**Maximum height during the flight**	**36.8 feet**	**47.32 feet**

From the above two observation table, we can verify that the value of CP and CG changes as the number of fins is changed, and the maximum height of flight is increased with the increase in the number of fins. The best-suited design for the fins needs to be trapezoidal and the number of fins must be four.

DESIGNING BY OPENROCKET SIMULATION SOFTWARE

The designs proposed in this paper was designed using OpenRocket simulation software. This is an open java based software. The software is used to design and also simulate the designed rocket. It allows to locate CP and CG and get the stability at the same time. The following are the proposed design and the maximum height achieved during the flight.

Design 1

Design 1	
Number of fins	3
Length of nose	2.67”
Diameter of nose	0.78”
Fin root chord(a)	3.0”
Fin tip chord (b)	1.5”

Fin semi span (s)	0.74”
Mid-chord length/ sweep length	2.635”
Sweep angle	74.3°
Xf	7.56”
Body length	7.89”
Centre of pressure	**7.48”**
Centre of Gravity	**6.694”**
Stability	0.787”
Maximum height of flight	30.8 feet

Design 2

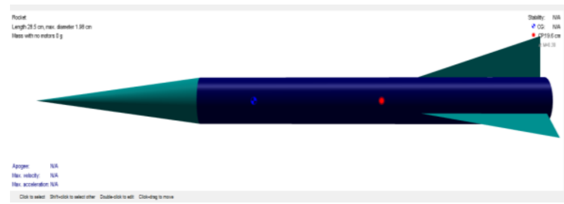
Design 2	
Number of fins	4
Length of nose	2.67”
Diameter of nose	0.78”
Fin root chord(a)	2.0”
Fin tip chord (b)	1.0”
Fin semi span (s)	0.57”
Mid-chord length/ sweep length	0.70”
Sweep angle	50.8°
Xf	8.53”
Body length	7.86”
Centre of pressure	**7.327”**
Centre of Gravity	**6.531”**
Stability	0.795”
Maximum height of flight	**144.0 feet**

Design 3

Design 3	
Number of fins	4
Length of nose	3.7”
Diameter of nose	0.78”
Fin root chord(a)	2.64”
Fin tip chord (b)	0”
Fin semi span (s)	0.585”
Mid-chord length/ sweep length	2.70”

Sweep angle	77.5°
Xf	8.6”
Body length	7.54”
Centre of pressure	**7.82”**
Centre of Gravity	**7.009”**
Stability	0.816”
Maximum height of flight	**42.8 feet**

Design 4



Design 4	
Number of fins	3
Length of nose	3.7”
Diameter of nose	0.78”
Fin root chord(a)	2.647”
Fin tip chord (b)	0”
Fin semi span (s)	0.677”
Mid-chord length/ sweep length	2.73”
Sweep angle	75.6°
Xf	8.5”
Body length	7.54”
Centre of pressure	**7.792”**
Centre of Gravity	**6.956”**
Stability	0.836”
Maximum height of flight	**131 feet**

4 CONCLUSION

It is clarified that for the stability of the rocket centre of mass and centre of pressure places an important role. For the centre of mass and centre of pressure, every component governs an important role. Fins play a very crucial role in stability as it is directly associated with the centre of pressure position. Increasing the number of fins gives rocket a proper balance. Trapezoidal shaped fins give more stability and make the design more aerodynamic that gives a sudden difference in maximum height of flight, which is from 25.59 feet to 144 feet with input force of just 0.5752N. Design 2 is the best-suited design for air propelled rocket. This paper can also be used to design an activity in space camps and outreach programs where the concepts of model rockets can be taught not only to young students but to every age group.

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