Design and Stability Analysis of a Model Rocket

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***Abstract*—Model rocketry serves as an educational and research tool for understanding aerodynamics, propulsion and stability principles. This study focuses on designing a stable model rocket while ensuring proper selection of materials and cost-effectiveness. Stability is determined by the relationship between the Center of Gravity (CG) and Center of Pressure (CP), with the Stability Margin (SM) acting as a key performance indicator. The CG is computed as the weighted average position of all rocket components, while the CP is determined using Borrowman Equations or aerodynamic simulations. A stability margin of 1.5 to 2.0 calibers is considered optimal for ensuring controlled flight without excessive weathercocking. The study also emphasizes material selection, balancing strength, weight and cost. Various materials for the body tube, nose cone and fins are analyzed based on durability and aerodynamic efficiency. Market research ensures cost-effective procurement of components, including engine selection, which directly influences thrust, burn time and altitude. By systematically applying NASA's standard stability methods, this research ensures the rocket meets essential safety and performance criteria. The findings contribute to a structured approach for designing and analyzing model rockets, making the process both scientific and practical.**

***Index Terms*—Aerodynamics, ballast weights, Barrowman equations, center of gravity (CG), center of pressure (CP), computational fluid dynamics (CFD), drag and lift, flight stability, launch dynamics, material selection, model rocket design, Newton's laws of motion, parachute deployment systems, propulsion systems, recovery mechanisms, rocket fins, rocket stability, solid-fuel engines, stability margin (SM), trajectory optimization.**

I. Introduction

Model rocketry is a specialized field of aerospace engineering that focuses on designing, constructing and launching small-scale rockets. These rockets are typically propelled by solid-fuel engines and are used for educational, research and experimental purposes. The key aspects of model rocketry include propulsion, aerodynamics, stability, material selection and trajectory optimzation. Each of these elements plays a crucial role in determining how a rocket performs under real-world conditions.

At its core, model rocketry is governed by Newton's laws of motion. The thrust produced by the engine must overcome the force of gravity, and once airborne, the rocket experiences aerodynamic forces such as drag and lift. The ability of a rocket to maintain a stable and predictable flight path depends on the proper alignment of its Center of Gravity (CG) and Center of Pressure (CP). Engineers must carefully balance these forces to ensure the rocket does not tumble mind-flight.

A key challenge in model rocket design is stability management. The stability of a rocket is determined by its Stability Margin (SM), which is calculated by measuring the distance between the CG and CP relative to the body diameter. If CG is too far back, the rocket will be unstable and may flip uncontrollably. If the Cp is too far forward, the rocket may be overstable, causing it to turn excessively into the wind (weathercocking). Achieving an optional SM between 1.5 and 2.0 calibers is essential for ensuring reliable performances.

Another crucial aspect of model rocketry is material selection. The rocket's body must be constructed from lightweight yet durable materials such as fiberglass, carbon fiber or aerospace-grade aluminum to withstand aerodynamic stress [5]. The nose cone, which is designed to minimize air resistances, is typically made of plastic or composite materials. Fins, responsible for aerodynamic stabilization, are often made of balsa wood, carbon fiber or reinforced polymers to provide strength without excessive weight.

Model rocketry is an intricate blend of physics, engineering and material science. Understanding stability principles, propulsion systems, aerodynamic behavior and material properties is critical for designing rockets that achieve controlled, high-altitude flights. By applying structured methodologies and leveraging advanced simulation tools, model rocket designers can create efficient, reliable and high-performing rockets tailored for research and educational applications.

II. Stability in Rocket Design

Rocket stability determines whether a rocket will maintain a controlled flight path or become erratic. Stability is influenced by the positioning of critical aerodynamic and mass properties, particularly the Center of Gravity (CG) and Center of Pressure (CP). The concept of stability in rocketry can be understood through static stability, which ensures the rocket returns to a stable path after disturbance. The application of momentum balance principles and fluid dynamics equations helps in the precise placement of CG and CP to optimize stability.

A. Center of Gravity (CG) Calculation

The Center of Gravity (CG) represents the point at which the rocket's mass is evenly distributed in all directions. It is computed using:

$$CG = \frac{\sum(w_i \times d_i)}{\sum w_i}$$

where w_i denotes the weight of each individual component, d_i represents its distance from a fixed reference point, generally the tip of the nose cone and $\sum w_i$ is the total weight of the rocket [2]. The accurate determination of CG is essential as it significantly affects the rotational inertia and overall

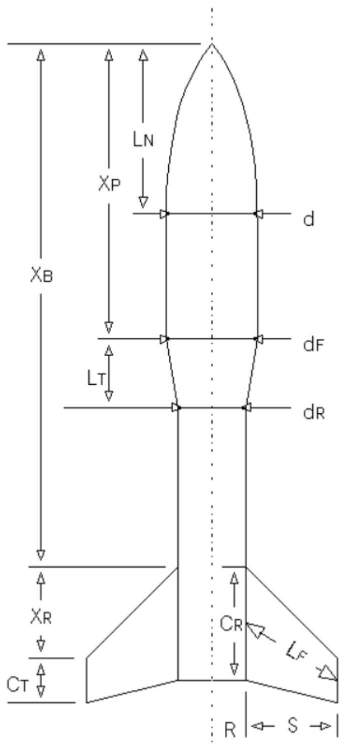

Fig. 1. Calculation of CP using Barrowman Equarions

maneuverability of the rocket. Adjusting the CG using ballast weights or internal redistributions can fine-tune the stability of the rocket for enhanced flight precision.

B. Center of Pressure (CP) Calculation

The Center of Pressure (CP) is the aerodynamic focal point where the net aerodynamic forces act. The CP is calculated using Barrowman Equations, which rely on the cumulative aerodynamic coefficients of each sections of the rocket. The general formula for CP is,

$$CP = \frac{\sum(A_i \times X_i)}{\sum A_i}$$

where A_i = reference aerodynamic area of each rocket section and, X_i = axial position of each section relative to a reference point

Using Barrowman Equestions, a much more detailed computation of center of pressure is discussed below [6]. Terms used in the equations are defined below and in the diagram (see Fig. 1) [6]

L_N = Length of nose
d = Diameter at base of nose
d_F = Diameter at front of transition
d_R = Diameter at rear of transition
L_T = Length of transition
X_P = distance from tip of nose to front of transition
C_R = Fin root chord
C_T = Fin tip chord
S = Fin semispan
L_F = Length of fin mid-chord line
R = Radius of body at after end
X_R = Fin root leading edge to fin tip
L_N = Distance from nose tip to fin root chord leading edge
N = Number of fins

Nose Cone Terms

$(C_N)_N$ = 2

For cone : X_N= 0.666 L$_N$

For ogive : X_N= 0.466 L$_N$

The normal force coeffiencient (C_N) for a nose is taken as 2 based on Newtonian Impact Theory and the assumption of a flat-plate approximation at hypersonic speeds. According to Newtonian Impact Theory, for high-speed flow (supersonic/hypersonic), the normal force is primarily due to the pressure difference across the surface. Newtonian theory assumes that fluid particles impacting a surface transfer their momentum perpendicular to the surface. If we approximate the nose as a flat surface perpendicular to the flow, the maximum normal force occurs when the surface is at a 90°angle of attack

Transition Section

$$(C_N)_T = 2\left[\left(\frac{d_R}{d}\right)^2 - \left(\frac{d_F}{d}\right)^2\right] \tag{1}$$

$$X_T = X_P + \frac{L_T}{3}\left[\frac{1-\frac{d_F}{d_R}}{1+\frac{d_F}{d_R}}\right] \tag{2}$$

Fin Terms

$$(C_N)_F = \left[1+\frac{R}{S+R}\right]\left[\frac{4N\left(\frac{S}{d}\right)^2}{1+\sqrt{1+\left(\frac{2L_F}{C_R+C_T}\right)^2}}\right] \tag{3}$$

$$X_F = X_B + \frac{X_R + (C_R + 2C_T)}{3(C_R + C_T)} + \frac{1}{6}\left[(C_R + C_T) - \frac{(C_R C_T)}{(C_R + C_T)}\right] \tag{4}$$

Finding the Center of Pressure

Sum up coefficients:

$$(C_N)_R = (C_N)_N + (C_N)_T + (C_N)_F \tag{5}$$

Find CP Distance from Nose Tip:

$$\bar{X} = \frac{(C_N)_N X_N + (C_N)_T X_T + (C_N)_F X_F}{(C_N)_R} \tag{6}$$

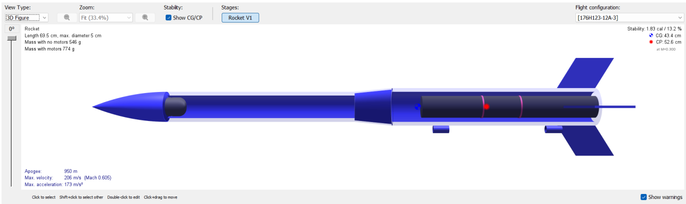

Fig. 2. Rocket designed in OpenRocket software

TABLE I
COMPARISON OF MATERIALS FOR ROCKET COMPONENTS

Material	Strength	Weight	Cost (per unit)
Fiberglass	High	Lightweight	$20
Carbon Fiber	Very High	Very Lightweight	$100
Aerospace Aluminum	Very High	Heavy	$50
Balsa Wood	Moderate	Very Lightweight	$5
Carbon Fiber (Fins)	Very High	Very Lightweight	$30
Reinforced Polymers	High	Moderate	$25
Plastic	Moderate	Lightweight	$10
Composite Materials	High	Lightweight	$80
Wood (Nose Cone)	Moderate	Heavy	$8

C. Stability Margin (SM) & Interpretation

The Stability Margin (SM) is a direct measure of how far the CG is ahead of the CP relative to the body diameter:

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

Where D represents the diameter of the rocket body. The SM provides an indicator of how predictable the flight characteristics will be:

- SM $<$ 1.0 - The rocket is aerodynamic unstable and prone to unpredictable motion.
- 1.0 $\leq$ SM $\leq$ 2.0 - The rocket is optimally stable, with a balance between stability and maneuverability.
- SM $\geq$ 3.0 - The rocket is overstable, causing it to veer into the wind (weathercocking), reducing altitude efficiency [1].

The designed rocket in Fig.2 has a Stability Margin of 1.84, making it a stable rocket [4]. Industry standards suggest a stability margin between 1.5 and 2.0 calibers, ensuring controlled yet efficient flight without excessive aerodynamic resistance. By understanding and applying these principles, model rocket designers can optimize performance, reduce failure risks, and ensure a smooth and controlled launch trajectory.

III. MATERIAL SELECTION & MARKET RESEARCH

The selection of materials for the rocket's body, fins, and nose cone is a critical aspect of the design process, as it directly impacts the rocket's weight, durability, and cost-effectiveness. For the body, fiberglass was chosen due to its excellent strength-to-weight ratio, durability, and affordability. Fiberglass is lightweight, which helps reduce the overall mass of the rocket, allowing for higher altitude and better performance. It is also highly durable, capable of withstanding the aerodynamic stresses and vibrations experienced during launch and flight. When compared to alternatives, fiberglass stands out as the most balanced option. Carbon fiber, for instance, is lighter and stronger but significantly more expensive, making it less practical for a cost-effective design. Aerospace-grade aluminum, while strong and durable, is much heavier than fiberglass, which would negatively impact the rocket's performance. Thus, fiberglass provides the best balance of lightweight construction, durability and cost-effectiveness for the body [5].

For the fins, balsa wood was selected because it is extremely lightweight, easy to shape and cost-effective. The fins primarily provide aerodynamic stabilization and balsa wood offers sufficient strength for this purpose without adding unnecessary weight. When compared to alternatives, balsa wood is the most practical choice. Carbon fiber fins are stronger and more durable but are also significantly more expensive and not necessary for this design. Reinforced polymers, while offering greater durability, are heavier and more costly than balsa wood. Therefore, balsa wood is the ideal choice for the fins, as it ensures the rocket remains stable during flight while keeping costs low [5].

The nose cone is made of plastic, which is lightweight, durable and easy to mold into an aerodynamic shape. Plastic is an excellent choice for minimizing drag, which is crucial for achieving optimal flight performance. When compared to alternatives, plastic is the most cost-effective and practical option. Composite materials like fiberglass or carbon fiber are stronger but more expensive and not necessary for the nose cone's function. Wooden nose cones, while potentially durable, are heavier and harder to shape precisely compared to plastic. Therefore, plastic is the best material for the nose cone, ensuring the rocket maintains its aerodynamic efficiency without unnecessary expense.

In summary, the materials selected—fiberglass for the body, balsa wood for the fins and plastic for the nose cone—were chosen based on their lightweight properties, durability, and cost-effectiveness. These materials provide the best balance of performance and affordability, ensuring the rocket can achieve its goals without compromising on quality or exceeding budget constraints. Alternatives like carbon fiber or reinforced polymers were considered but rejected due to their higher costs and lack of significant performance benefits for this design. This careful selection of materials ensures that the rocket is both functional and cost-effective, making it suitable for educational and research purposes.

graphicx

IV. ENGINE SELECTION & PRICING

The Cesaroni Technology 176H123-12A-3 motor is selected for this rocket design due to its high-performance capabilities, reliability and suitability for advanced model rocketry. This motor is a solid rocket motor designed for high-altitude flights and research purposes [3]. It provides 176 Newton-seconds (N-s) of total impulse, which is significantly higher than smaller engines like the Estes C6-5, which offers only 10 N-s.

This high total impulse makes the Cesaroni motor ideal for achieving greater thrust and altitudes exceeding 1,000 meters, depending on the rocket's design and weight. The motor has a burn time of approximately 1.8 seconds, providing sufficient thrust to propel the rocket efficiently while maintaining stability during flight. Cesaroni motors are renowned for their consistent performance and safety, making them a reliable choice for advanced rocketry projects.

When compared to other engines, the Cesaroni 176H123-12A-3 stands out for its high total impulse and altitude capabilities. For example, the Estes C6-5, a popular choice for beginner and intermediate rocketry, offers only 10 N-s of total impulse and is limited to altitudes of around 300 meters. While the Estes engine is cost-effective and easy to use, it lacks the power and performance needed for high-altitude or research-oriented missions. Another alternative is the Aerotech F44-4W, which provides 80 N-s of total impulse and a burn time of 1.6 seconds. While the Aerotech motor is more powerful than the Estes C6-5, it still falls short of the Cesaroni 176H123-12A-3 in terms of total impulse and altitude potential. The Cesaroni motor's ability to deliver 176 N-s of total impulse makes it a superior choice for achieving higher altitudes and greater thrust, which are critical for this project's goals.

The cost of the Cesaroni 176H123-12A-3 motor is approximately \$120 which is higher than smaller engines like the Estes C6-5 (\$15) or Aerotech F44-4W (around \$50) [3]. However, the higher cost is justified by the motor's performance, reliability and suitability for advanced missions. The Cesaroni motor's ability to propel the rocket to altitudes exceeding 1,000 meters makes it an excellent choice for research and high-altitude applications. Additionally, its consistent performance ensures that the rocket achieves a stable and predictable flight path, reducing the risk of failure.

What makes the Cesaroni 176H123-12A-3 motor stand apart is its combination of high total impulse, reliability and altitude capabilities. Unlike smaller engines, this motor is designed for advanced rocketry, making it ideal for research and educational purposes. Its high thrust and longer burn time allow the rocket to achieve greater altitudes, while its consistent performance ensures a stable and controlled flight. Furthermore, the motor's safety features and ease of use make it a practical choice for advanced rocketry projects.

In conclusion, the Cesaroni 176H123-12A-3 motor is selected for this rocket design because of its high total impulse, reliability and ability to achieve high altitudes. While it is more expensive than smaller engines like the Estes C6-5 or Aerotech F44-4W, its performance justifies the cost for advanced research and high-altitude missions. The motor's consistent performance, safety features and ease of use make it an excellent choice for this project, ensuring that the rocket achieves its goals efficiently and reliably.

Fig. 3. Cesaroni 176H123-12A-3 motor

V. Detailed Component List & Cost Analysis

The following section provides a comprehensive breakdown of all components used in the rocket design, including their material types, suppliers, unit prices, and total costs. This detailed analysis ensures transparency in the selection of materials and components, while also highlighting the cost-effectiveness of the design. By systematically listing each component and its associated costs, we can better understand the financial requirements of the project and make informed decisions to optimize the rocket's performance and budget.

TABLE II
Component List and Cost Analysis

Component	Material Type	Supplier / Market Source	Unit Price	Quantity	Total Cost
Body Tube	Fiberglass	Fiberglass World	\$20	1	\$20
Fins	Balsa Wood	Woodcraft	\$5	3	\$15
Nose Cone	Plastic	Plastic Suppliers	\$10	1	\$10
Engine	Cesaroni 176H123	Cesaroni Technology	\$120	1	\$120
Total					**\$165**

Total Cost in Indian Rupees (INR)

The total cost of the rocket components is \$165. Assuming an exchange rate of 1 USD = 86 INR, the total cost in Indian Rupees is:

$$165\,\text{USD} \times 86\,\text{INR/USD} = \boxed{14{,}190\,\text{INR}}$$

VI. Conclusion

The design and stability analysis of the model rocket presented in this microthesis demonstrate a structured and scientific approach to creating a high-performance, cost-effective rocket suitable for educational and research purposes. By carefully selecting materials such as fiberglass for the body, balsa wood for the fins, and plastic for the nose cone, the rocket achieves an optimal balance of lightweight construction, durability, and cost-effectiveness. The choice of the Cesaroni Technology 176H123-12A-3 motor further enhances the rocket's performance, enabling it to achieve altitudes exceeding 1,000 meters with a total impulse of 176 N-s, making it ideal for advanced rocketry applications.

The stability analysis, guided by NASA's standard methods, ensures that the rocket maintains a stable flight path with a Stability Margin (SM) of 1.84 calibers, well within the optimal range of 1.5 to 2.0 calibers. This stability is achieved through precise calculations of the Center of Gravity (CG) and Center of Pressure (CP), ensuring controlled flight without excessive weathercocking or instability.

The detailed component list and cost analysis provide transparency in the selection of materials and components, highlighting the project's cost-effectiveness. With a total cost of $165 (approximately 14,190 INR), the rocket is both affordable and high-performing, making it accessible for educational and research institutions.

In conclusion, this microthesis contributes to the field of model rocketry by providing a structured methodology for designing, analyzing, and optimizing model rockets. The findings underscore the importance of material selection, stability analysis, and cost-effectiveness in achieving successful rocket designs. Future work could explore advancements in reusability, hybrid propulsion systems, and increased payload capacity to further enhance the rocket's capabilities. This project not only advances the understanding of rocketry principles but also serves as a practical guide for aspiring rocket designers and researchers.

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