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Low-Altitude Rocket Stability Under Various Fin Cant Angles and Cross Wind Speeds

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ABSTRACT

This paper undertakes a comprehensive aerodynamic analysis of low-altitude rockets. The stability of rockets launched from low-latitude regions presents unique challenges, such as the presence of trade winds and localised turbulence, which may potentially lead to deviations from the intended flight path and an increased risk of structural failure. The study focuses on the R3KM rocket and investigates two distinct configurations: a three-fin rocket canted at 0°, 2.5°, and 5°, as well as a four-fin rocket canted at the same angles. To assess the rocket's stability during flight, numerous simulations have been conducted across a variety of wind velocities. Concurrently, the dynamic stability analysis focuses on the rocket's ability to respond effectively to external disturbances such as crosswind. Significant emphasis is placed on refining the fin design to optimise both aerodynamic efficiency and stability. The use of OpenRocket software allows for simulations, guiding the iterative process of improving the rocket's aerodynamic configuration. The findings from this study indicate that canted fins enhance the rocket's stability as wind speeds increase. The three-fin R3KM configuration attains greater apogees at about 5%, however, the four-fin version exhibits enhanced aerodynamic stability at elevated wind speeds (i.e., 2 m/s to 4 m/s higher critical wind speed), depending upon the cant angle. These results suggest that while the three-fin design may reach greater heights, the four-fin design provides better stability in challenging wind conditions. This study's findings are anticipated to enhance the efficiency and reliability of rockets, thereby advancing the field of rocket aerodynamics.

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INTRODUCTION

Aerodynamic stability in low-altitude rockets refers to the capability of a rocket to maintain a balanced and controlled trajectory within the earth's lower atmosphere. The design of unguided rockets played a pivotal role in achieving aerodynamic stability. Unguided-sounding rockets lack active guidance or control devices, making them at risk of instability caused by factors like air resistance and wind (Yılmaz & Cihan, 2024). Model rockets exhibit a wide range in dimensions, form, mass, and fabrication, ranging from precise scale models of professional rockets to lightweight competition models. Achieving aerodynamic stability is crucial for the successful ascent and controlled flight of the rocket, especially during the initial stages of its journey when it is subjected to atmospheric forces.

For the rocket to achieve and maintain stability during its flight, it is essential that there exists a distance of at least one full diameter of the rocket's body between the centre of pressure and the centre of gravity (Özel et al., 2023). This spatial relationship is crucial because it ensures that the aerodynamic forces acting on the rocket can effectively counterbalance any disturbances that may occur during flight. If the centre of pressure and the centre of gravity are positioned too closely to each other, the rocket may become dynamically underdamped (Negahban, 2019). This condition can lead to oscillations that are not adequately controlled, resulting in a lack of stability and potentially causing the rocket to veer off its intended path. Likewise, if the distance between the centre of pressure and the centre of gravity is excessively large, the rocket becomes unstable, which may ultimately lead to a catastrophic failure or cause it to fall uncontrollably. For the rocket to achieve a stable and successful flight trajectory, it is imperative that the centre of pressure is located behind the centre of gravity (Yarce et al., 2017). This arrangement allows for a natural restoring force that helps the rocket return to its intended flight path after any disturbances, thereby enhancing overall flight stability. The behaviour of the rocket and how it rotates in response to the wind are best described by the rocket’s static stability margin (Guerrero et al., 2018).

The fins of an unguided rocket play a crucial role in stabilising the rocket’s flight trajectory (Bunkley et al., 2022). Attaching tail fins to the end of the rocket positions its centre of pressure towards the rocket engine located behind the centre of gravity (Fraley, 2018). The rocket may tilt significantly from its current attitude depending on a minor wind gust or some other disruption (Niskanen, 2013). When this occurs, the rocket centerline is no longer parallel to the velocity of the rocket. The rocket centerline changes in direction from parallel to the rocket's velocity at this event. Flying at an angle of attack α is the state in which the angle α is the one between the velocity vector and the rocket centerline. Adding fins to a rocket serves the purpose of ensuring stability throughout its flight, enabling it to sustain its orientation and follow its intended trajectory (Ujjin et al., 2021). When a stable rocket ascends at an angle of attack, its fins generate a moment to rectify the rocket's trajectory.

The design of the fin is crucial as it directly impacts the stability of the rocket during its flight (Adnan et al., 2023). The physical characteristics of the rocket's fins, such as their shape, size, and material, significantly influence the overall stability and performance of unguided rockets (Barbosa & Guimarães, 2012; Pektaş et al., 2019; Schoch, 2023; Zhang et al., 2016). Fins that are too small or improperly shaped may not generate sufficient aerodynamic forces to counteract disturbances, leading to increased instability during flight. Conversely, excessively large fins can introduce additional drag, which may hinder the rocket's ascent and overall efficiency. Understanding the optimal fin design, including the cant angle, is essential for maximizing stability while minimizing drag. This balance is particularly critical in low-altitude flights, where atmospheric conditions can vary rapidly and unpredictably.

Canted fins play a significant role in rocketry analysis. A study asserts that the rolling channel remains uncontrolled during a guided spinning rocket's flight. However, the canted tailfins are crucial in generating rolling torque, which then balances with the rolling damping torque. This equilibrium helps in maintaining a stable spinning rate, simultaneously aiding the rocket's stability during launch (Shi et al., 2021).

A recent study has examined the relationship between aerodynamic coefficients and various fin arrangements, with a particular focus on the cant angle (Sankalp et al., 2022). Three-dimensional,

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incompressible simulations were conducted on various models of sounding rockets using the commercial computational fluid dynamics (CFD) software FLUENT. The study found that an increase in the angle of attack results in a very non-significant increase in the coefficient of rolling moment. Hence, the moment coefficient over drag coefficient ratio decreases with an increase in angle of attack for a given fin. Changing the error function under optimisation was observed to have a major impact on the resultant fin drag coefficient but very little effect on the body tube drag coefficient. It is considered that, in this sense, the fin-tumbling model exhibits more inaccuracy (Niskanen, 2013).

Despite the critical role that fin design plays in the stability and control of rockets, there exists a notable gap in the literature regarding the influence of fin cant angle on rocket performance in crosswind conditions. While previous studies have explored various aerodynamic factors affecting rocket flight, the specific interaction between fin cant angle and crosswind speed remains under-researched. This lack of comprehensive understanding poses significant challenges for engineers and designers aiming to optimize rocket stability and trajectory in real-world launch scenarios, where crosswinds are a common occurrence. Therefore, this research aims to investigate the effects of varying fin cant angles on rocket performance under different crosswind speeds, ultimately contributing to the development of more reliable and efficient rocket designs.

METHODOLOGY

In this examination of the stability of a model rocket (named R3KM rocket), a mathematical approach was applied to evaluate the performance of a rocket with three different fin cant angles (0°, 2.5°, and 5°) and flying under crosswind conditions (wind speed varying from 0 m/s to 20 m/s). We selected these angles due to their potential to generate a significant roll moment while minimizing drag. We resolved the Barrowman equations, a mathematical technique for forecasting rocket aerodynamics during flight, using the OpenRocket software. OpenRocket is a widely employed open-source software tool for designing and simulating model rockets, presenting a user-friendly interface for enthusiasts. The simulation also provides maximum velocity, mass, acceleration, and stability (Bunkley et al., 2022). The OpenRocket software has been rigorously evaluated against experimental data, demonstrating a 98.74% accuracy in predicting the rocket's apogee and lateral distance when compared to a GPS system (Caballes et al., 2021).

In this study, the independent variables consist of canted angle fin and Mach number, while the dependent variables include apogee, spin rate, drag force, and other results arising from the manipulation of inputs. It is noted that Open Rocket Simulator is utilised to perform apogee and stability calculations for a standard model rocket (Pektaş et al., 2019). The introduction of canted angle finned design influences pressure distribution around the rocket body and its aerodynamic loading. The Mach number represents the rocket's speed relative to the speed of sound in the fluid. Throughout the experiments, the material, weight, dimensions of the rocket body, and nose cone design remain uniform.

Rocket stability is a focal concern in design, with the centre of gravity easily calculable, but the centre of pressure presents challenges. John Barrowman's equations and guidelines have provided a practical approach to predict the centre of pressure based on aerodynamic geometry (Barrowman, 1967). By entering the specifications of the model into OpenRocket, the equations were solved to determine the location of the centre of pressure. The software allows the creation of various fin designs, facilitating observation of their impact on static and dynamic stability during flight.

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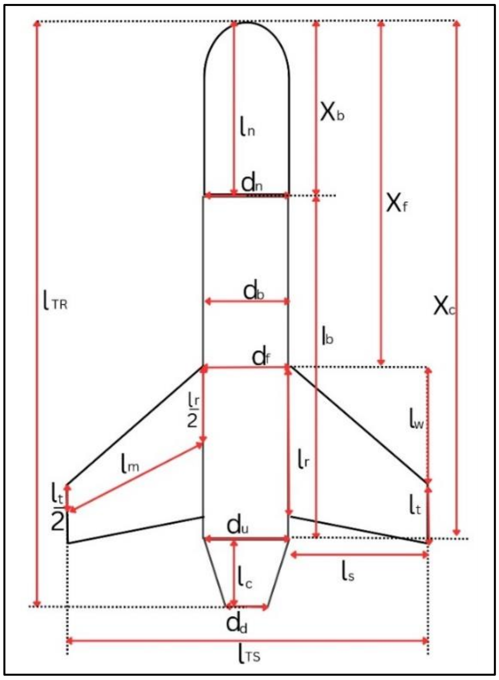

Fig. 1. Dimension of the typical rocket (adopted from (Barrowman, 1967)).

l_n	Length of nose cone	l_r	Fin root-chord
l_s	Fin span	l_m	Fin mid-chord
l_{TR}	Length of the rocket	l_b	Body tube
lw	Length between fin root-chord and tip-chord	l_t	Fin tip-chord
l_{TS}	Length between tip-chord to another tip-chord	l_c	Length of conical change
d_n	Diameter nose cone	d_u	Upstream diameter of conical change
d_d	Downstream diameter of conical change	d_b	Diameter of the body tube
X_c	Distance between nose cone tip and upstream point	d_f	Diameter of the body tube at fin's location
X_b	Length between nose cone tip to the upstream body tube	X_f	Length between nose cone tip to the fin leading edge

In rocketry, there are two main ways to figure out how air affects a rocket's flight: first, by estimating how much lift its fins create (called the normal force coefficient, C_N, and second, by estimating how much air resistance it faces (known as the coefficient of drag, C_D, John Barrowman came up with equations to help figure out these values, especially for smaller rockets. However, these equations rely on a few basic assumptions (Box et al., 2009):

(i) The rocket's angle of attack is shallow ($\alpha < 10°$).
(ii) Compressibility effects are insignificant, meaning Mach number (Ma) is less than 0.4.
(iii) Viscous forces are not significant.
(iv) Lift forces on the rocket's body tube can be disregarded.
(v) The airflow over the rocket remains smooth and steady.
(vi) The rocket is slender compared to its length.
(vii) The rocket's nose tapers smoothly to a point.

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(viii) The rocket is a symmetrical, rigid body.
(ix) The fins are thin, flat plates.

The normal force on the rocket is given by Equation 1,

$$F_N = \frac{1}{2}\rho V^2 A_r C_N \tag{1}$$

where A_r is the cross-sectional area of the rocket at the base of the nosecone, ρ is the atmospheric density, V is the rocket's apparent velocity and C_N is the aerodynamic normal force coefficient. The Barrowman equations were utilised to ascertain the centre of pressure for a given rocket geometry. Equation 2 was employed to compute the centre of pressure of the rocket:

$$\bar{x} = \frac{(C_N)_n \bar{x}_n + (C_N)_{fb} \bar{x}_f}{C_N} \tag{2}$$

The stability derivative for a rocket's nosecone is 2 if the shape of the nosecone is either conical, ogive or parabolic. In this study ogive shape is utilised, thus the location of the centre of pressure of the nose cone is $\bar{x}_n = 0.466 l_n$. The following equations are for the entire fin set and are valid for configurations with 3 or 4 trapezoidal fins (Box et al., 2009). Since the trapezoidal finest are used in this study, the stability derivative is given by Equation 3:

$$(C_N)_{fb} = K_{fb} \frac{4n(\frac{l_s}{d_s})^2}{1 + \sqrt{1 + (\frac{2l_m}{l_r + l_t})^2}} \tag{3}$$

where K_{fb} is a coefficient that considers an increase in the normal force due to interference effects between the fin and the body.

$$K_{fb} = 1 + \frac{\frac{d_f}{2}}{(l_s + \frac{d_f}{2})} \tag{4}$$

where d_f is the diameter of the body tube at the fin's location. The location of the centre of pressure for a trapezoidal finset is given by,

$$\bar{x} = \bar{x}_f + \frac{l_m(l_r + 2l_t)}{3(l_r + l_t} + \frac{1}{6}[l_r + l_t - \frac{l_r l_t}{l_r + l_t}] \tag{5}$$

where $\bar{x}_f$ is the length between the nose cone tip and the point where the fin leading edge meets the body tube.

Table 1 presents the nosecone and body specifications of the model representative rocket and the parameters employed in the analysis of rocket stability. For fin stabilisation, the 3 and 4 trapezoidal fin sets are analysed for cant angles of 0°, 2.5°, and 5°. Other geometrical parameters remain unchanged. Table 2 presents the parameters for the 3 and 4 trapezoidal fin sets.

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Table 1. Nosecone and body parameters used for both 3 and 4 canted fin sets

Component	Parameter	Unit	3 Fins	4 Fins
Nosecone	Length	cm	20	20
	Based diameter	cm	8	8
	Wall thickness	cm	0.2	0.2
Body tube	Overall length	cm	20	20
	Max diameter	cm	109	109
	Mass with motor	g	5208	5262
	Mass without motor	g	1447	1501

Table 2. Parameters used for 3 trapezoidal fin set

Component	Parameter	Unit	Value
	Root chord	cm	10
	Tip chord	cm	6
Fin	Height	cm	12
	Sweep length	cm	15.62
	Thickness	cm	0.3

The analysis of aerodynamic stability on rocket performance was carried out using OpenRocket software to examine the effects of canted fins under various wind speeds. The wind speed ranged from 0 m/s to 20 m/s to observe the rockets' stability behaviour. Turbulence intensity was maintained at 10%, and wind direction was fixed at 90° to minimise other disturbances during the flight simulation. The standard deviation of wind speed was also set in accordance with the wind speed.

RESULTS AND DISCUSSION

Effect of Canted Fins to Aerodynamic Stability

The R3KM rocket, equipped with both 3 and 4 fins, was simulated at various wind speeds to observe its apogees. Each canted fin configuration was analysed, revealing that as the cant angle increased, the aerodynamic stability also improved, allowing the rocket to withstand higher wind speeds. Fig 2 and Fig 3 illustrate the comparison of 0°, 2.5°, and 5° canted fins for both the respective 3-fin and 4-fin configurations of the R3KM.

Both the 3-fin and 4-fin configurations exhibit a similar pattern where canted fins improve the rocket's stability, enabling them to reach their expected apogees. The greater the fin angle, the higher the wind speed the rocket can endure before failing. This is because canting the fins generates a spin motion, creating an axial aerodynamic moment. This aligns with a study where canted fins, installed at the rocket's tail, provide lift and roll moment (Shi et al., 2021). At higher wind speeds, the canted fins produce rolling torque, balanced by rolling damping torque, maintaining a stable spin rate along the trajectory. Fins with cant angles are commonly used in sounding rockets and missiles to reduce instability (Sankalp et al., 2022).

Fig 2 and Fig 3 also show that adding more fins decreases the apogee. This is due to the increased surface area in contact with the air, which increases skin friction drag. The increased drag resulted in a lower net thrust, reducing the rocket's apogee. A further discussion on drag will be reported in the subsequent subsection. However, more fins have also been shown to increase stability, where the critical wind speed (a minimum wind speed at which the rocket tumbles) increases with the number of fins.

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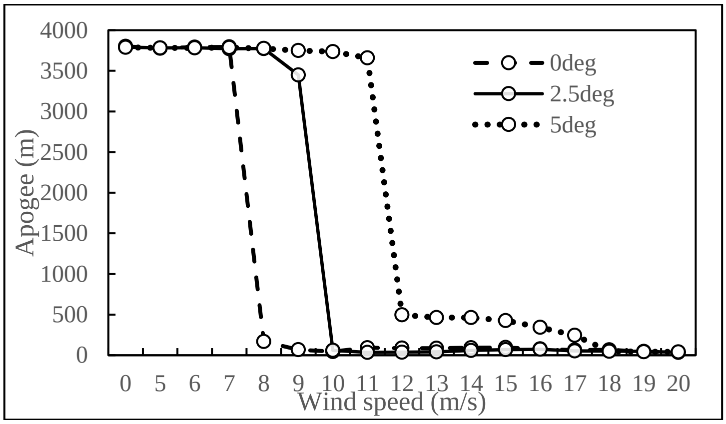

Fig. 2. 3 fin-configuration with various cant angle and wind speed.

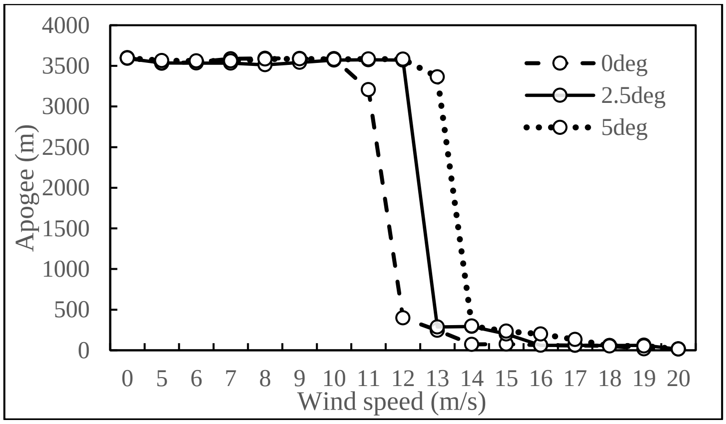

Fig. 3. 4 fin-configuration with various cant angle and wind speed.

Fig 4 compares the 4-fin configuration at a wind speed of 10 m/s, showing how canted fins produce roll motion during ascent to reach the apogee. Fig 4 illustrates that a fin without canting produces a negligible amount of roll rate. This outcome is anticipated due to the geometric symmetry of the fin structure, resulting in a symmetrical pressure distribution. However, canted fins provide a rotational motion on the rocket during ascent, with a greater cant angle resulting in a more rapid spinning motion, as shown in Fig 5. This spin generates gyroscopic stability, similar to a spinning top. The angular momentum from the spin resists changes in the rocket's orientation, making it less prone to being knocked off course by the wind. The gyroscopic effect provides an additional stabilising force that helps the rocket maintain its trajectory. Therefore, the higher the spin rate is induced by the canted fins, the greater the gyroscopic stability.

It is also interesting to note that the stability margin during flight is mostly unaffected by the spin rate, as shown in Fig 6. This figure illustrates that the stability margin experiences a significant rise when the rocket accelerates during the initial period of flight. This results from the increasing aerodynamic forces acting on the rocket, causing the centre of pressure to move towards the rear of the body. Moreover, when fuel is consumed, the centre of mass shifts towards the nose of the rocket, so enhancing the stability margin. The stability margin stabilises as the rocket ceases acceleration and diminishes as aerodynamic forces become less prominent.

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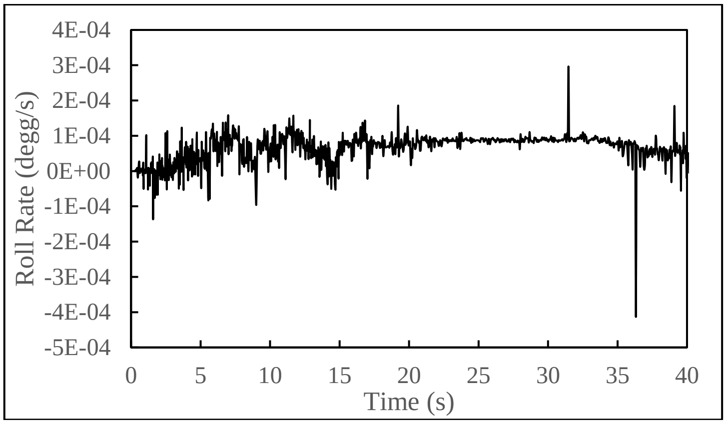

Fig. 4. Roll rate time history for 0° fin, 4 fin-configuration.

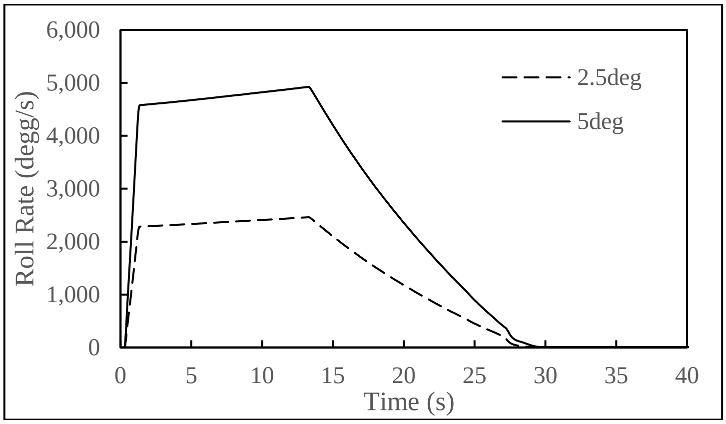

Fig. 5. Roll rate time history for 2.5° and 5° cant fin, 4 fin-configuration.

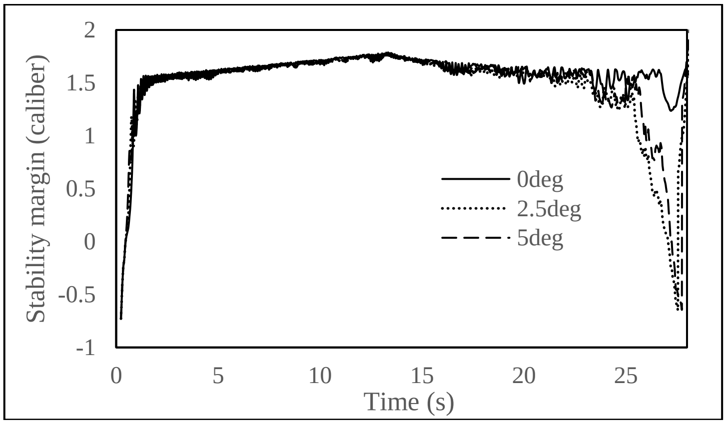

Fig. 6. Stability margin during flight at a wind speed of 10 m/s.

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Effect the Number of Fin to Apogee

The maximum height reached by the rocket is one of the main objectives in designing the rocket. The study continues by observing the apogee of R3KM from 3 and 4 fin configuration with various canted fin of 0°, 2°, and 5°. Table 3 summarizes the apogee and maximum acceleration of 3 and 4 fin configurations at different fin cant angles.

Table 3. Acceleration and apogee of 3- and 4-fin configurations at 0 m/s wind speed

	3 fin configurations		**4 fin configurations**	
Cant Angle (°)	Maximum acceleration (m/s^2)	Apogee (m)	Maximum acceleration (m/s^2)	Apogee (m)
0	208	3800	205	3600
2.5	213	3792	210	3591
5	213	3789	210	3595

The table indicates that for each cant angle of 0°, 2.5°, and 5°, the 3-fin configuration achieves a slightly higher apogee compared to the 4-fin configuration. This is due to several aerodynamic and physical factors. It is noted that the additional fin in a 4-fin configuration adds extra weight. Although this difference may seem minimal, even small increases in weight can significantly impact the rocket's acceleration and maximum altitude.

Table 3 also presents the maximum acceleration of 3- and 4-fin configurations with 0°, 2.5°, and 5° canted fins at 0 m/s wind speed. The maximum acceleration of all cant angle 4 fin configuration shows slight lower value which resulted of slight lower apogee. The following expression can be shown to be a good approximation for the acceleration of the rocket.

$$\mathrm{a} = \frac{v_e}{m}\frac{\Delta \mathrm{m}}{\Delta \mathrm{t}} - \mathrm{g} \tag{6}$$

where a is the acceleration of the rocket, ve is the escape velocity, m is the mass of the rocket, Δm is the mass of the ejected gas, and Δt is the time in which the gas is ejected.

A rocket’s acceleration depends on three major factors, consistent with the equation for acceleration of a rocket, the exhaust velocity v_e of the gases relative to the rocket, the rate at which the rocket burns its fuel and the rocket's mass Since the design parameter and motor of the R3KM for both 3 and 4 fin configurations are the same except the number of fins, which impacts the difference in weight, mass is the main factor in the acceleration of the rocket. The smaller the rocket’s mass (all other factors being the same), the greater the acceleration. It explains why a 3-fin rocket can achieve higher velocities with the same thrust, leading to a higher apogee.

Drag

Two main mechanisms lead to drag forces: skin friction and air pressure distribution around the rocket. A 4-fin rocket generally experiences greater drag compared to a 3-fin rocket due to several aerodynamic and physical factors. Adding a fourth fin increases the total surface area exposed to airflow, resulting in higher skin friction drag because there is more surface for air to rub against (as summarized in Table 4).

Table 4. Total drag & friction drag coefficients

Number of fins	Launch (CD/CF)	Apogee (CD/CF)
3	1.33/1.14	1.01/0.76
4	1.44/1.08	1.11/0.81

The skin friction coefficient is characterised as the drag coefficient resulting from friction, with the reference area encompassing the complete wetted surface of the rocket, including both the body and fin areas in contact with the airflow. With more fins, the rocket's overall profile becomes bulkier, increasing

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form drag, which is the resistance created by the rocket's shape moving through the air. For 3-fin and 4-fin configurations, the friction drag coefficient and drag coefficient over time are illustrated in Fig 7 and Fig 8.

It shows that the 3-fin configuration generates a slightly lower drag coefficient than the 4-fin configuration. Additional sources of drag include interference between the fins and the body and vortices generated at the fin tips when flying at an angle of attack (Niskanen, 2013). More fins mean more vortices, which create additional turbulent airflow, thereby increasing induced drag. While 4 fins provide greater aerodynamic stability, the trade-off is increased drag for the reasons mentioned above.

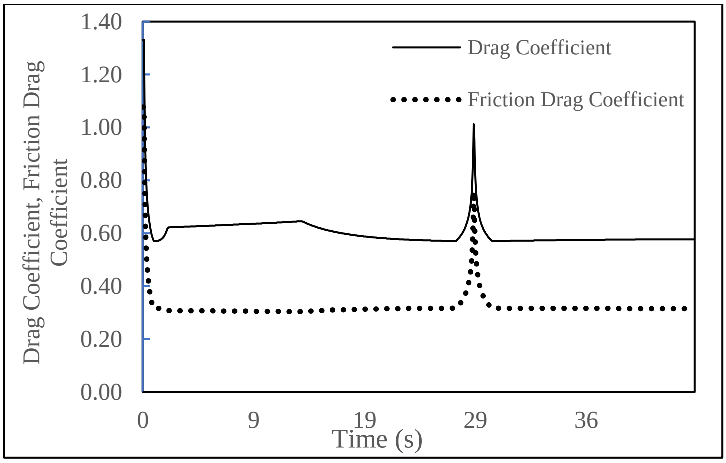

Fig. 7. 3 fin configurations; drag, and friction drag coefficient over time.

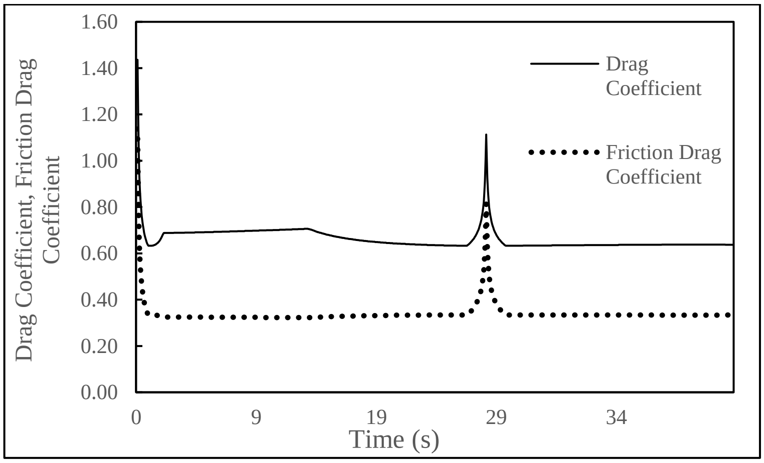

Fig. 8. 4 fin configurations; drag, and friction drag coefficient over time.

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CONCLUSION

The R3KM rocket, featuring both 3 and 4 fins, was simulated at various wind speeds. It is concluded that canting the fins enhances the stability margin, enabling the rocket to withstand wind speeds up to 50% greater, thanks to the induced spin's gyroscopic stability. Consequently, the rocket's ability to withstand a wider range of circumstances before experiencing instability is crucial for achieving successful launches. Furthermore, canted fins can be designed to perform well under different launch conditions, such as varying altitudes and speeds. This adaptability makes them suitable for a wide array of unguided rocket applications. The study also observed that the 3-fin configuration achieved an average of 5% higher apogee than the 4-fin configuration due to its lighter weight and lesser skin friction drag. A lighter rocket accelerates more, leading to a higher apogee. More fins also lead to more vortices, increasing induced drag. Most importantly, the use of canted fins may simplify the overall rocket design by reducing the requirement for sophisticated guidance systems. Implementing this approach can reduce production expenses and enhance the affordability of the rockets for diverse applications.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHOR’S CONTRIBUTIONS

The authors confirm the equal contribution in each part of this work. All authors reviewed and approved the final version of this work.

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