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The Effect of Moveable Fins on Trajectory and Aerodynamic Characteristics of Model Rockets

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Abstract

The application of the fins on the rocket are necessary to achieve optimal flight performance. However, the appearance of gust wind can affect the stability of the rocket during flight. To minimize instability, the fins are designed to be adjustable by changing the fin cant angles. This study aims to investigate the effect of different cant angles on rocket's trajectory and aerodynamic characteristics through computer simulation. The Open Rocket software is used to conduct the simulations. The range of cant angle in this study is from 0° to 15° and the Clipped Delta fin design is chosen for this study. The launch condition is all the same for all the model rockets and the launch site's latitude and longitude was based on Parit Raja location. The trajectory characteristics were evaluated through simulations of altitude versus position east of launch, altitude versus position north of launch, and altitude versus lateral distance. Meanwhile, the aerodynamic characteristics were evaluated through simulations of stability margin and drag force over time. This study found that the maximum altitude for each model rocket is decreasing as the cant angle increases. Different fin's cant angles slightly alter the trajectory characteristic of model rockets, but they do not significantly impact the overall stability and drag characteristics during critical phases of flight. Higher cant angles resulted in shorter horizontal and lateral distances from the launch site to the apogee, suggesting a more vertical trajectory.

1. Introduction

Computer simulations have emerged as an invaluable tool in the field of rocket design and engineering. These computational techniques enable researchers and engineers to extensively evaluate and optimize various rocket configurations before committing to physical prototyping and testing. Through simulations, critical design parameters can be systematically analyzed to understand their impacts on trajectory, stability, aerodynamic performance, and other key factors influencing a rocket's flight behavior. This approach offers a cost-effective and efficient means of exploration, allowing for virtual experiments that mitigate the risks and resource demands associated with physical testing.

Sounding rockets launch payloads into Earth's upper atmosphere, where they collect data for scientific purposes and descend back to Earth using a parachute. These rockets are necessary for numerous scientific fields and are currently in high demand as the most affordable platform for upper-atmosphere research [1-3].

During the flight of the rocket, various perturbations may arise contributing to disturbing the rocket and deflecting it from the intended flight path. One of the perturbations or disturbances is from the external environment, like the presence of gusty winds. The gust wind that crosses the rocket will increase the angle of attack of the rocket. If this situation continues, the increasing deflection angle of the perturbed rocket will make the rocket unstable and lead to an unpredictable trajectory of the unguided rocket after launching. However, we can increase the stability of the rocket by making the fins moveable by determining the cant angle of the rocket fins.

"Unguided" means that no active control is exerted to keep the rocket on a predefined path. The concept of unguided rockets is well-established in the field of rocketry. Unguided rockets are rockets that do not have any active control systems to keep them on a predefined path. Instead, they rely on passive guidance systems, such as fins, to maintain stability and control during flight [4]. Research conducted by Anandaraj et. al. [5] has shown that the stability of unguided artillery rockets can be improved by reducing the out-of-plane moment through the use of curved wrap-around fins with reduced fin cant angles. The study employed wind tunnel tests and trajectory simulations to visualize the improvement in the performance of the rocket. Flight tests of the rocket with reduced fin cant angle were carried out, and the configuration achieved the desired range with excellent flight stability and consistency [5].

There have only been a few studies done thus far to simplify the rocket design process and comprehend the physics involved. Asilyazici conducted a detailed explanation of model rocket motors, rocket construction, and flight analysis techniques in his study on rocket design [6]. Niskanen, as part of his M.Sc. thesis, created Open Rocket Simulator, an open-source model rocket simulation program [7]. Model rockets have recently been used to teach engineering students. Brewer et al. [9] utilised the model rockets for propellant analysis, whereas Campbell et al. [8] utilised them to simulate flight trajectories. Research conducted by Sankalp et. al. [10] has shown that fins with cant angles are used to provide a rolling moment in sounding rockets and missiles to minimize instability.

The purpose of this study is to investigate the effect of different cant angles on rocket trajectory and aerodynamic characteristics using model rockets with different cant angles. The scope of this study encompasses the following: 1) Utilization of the Open Rocket simulator to investigate the impact of varied cant angles on rocket trajectory characteristics. 2) investigation of cant angles ranging from 0°, 1°, 2°, 3°, 4°, 5°, 10°, and 15° for the rocket fins. 3) Simulation of launch conditions under normal weather conditions within the Open Rocket environment. 4) Simulation of launch site based on the latitude and longitude of Parit Raja, Johor. 5) Ensuring that the maximum altitude achieved by each model rocket exceeds 2500 feet. Furthermore, this study aims to contribute to the growing body of knowledge in rocket design and optimization, specifically in the context of fin configuration and its impact on trajectory and aerodynamic characteristics.

2. Methodology

This section explains the methodology used to achieve the objectives of the study and presents the detailed components of the base model rocket. The model rocket with movable fins, i.e. the cant angle can change from 0° - 15° cant angles is designed using the Open Rocket software. The design chosen is the Clipped Delta Fin, and its parameters will be described. Every model rocket with a different cant angle is set to have the same launch conditions before running the simulations.

2.1 Rocket Design

This study designed the rocket body to be 45 inches long with an outer diameter of 3 inches and an inner diameter of 2.93 inches, as shown in Fig. 1. Hence, the length ratio is 15:1 from its diameter. The fins are positioned at the rear end of the rocket to ensure that the centre of pressure (CP) is located behind the rocket's centre of gravity (CG). This configuration provides stability to the rocket, helping to keep it steady during flights. The fins are set to be movable, i.e. the fins' cant angle can be adjusted. The cant angle ranges from 0° to 15° in this study. As depicted in Fig. 2, the definition of the fin's cant angle is illustrated for 0°, 5°, 10° and 15° angles.

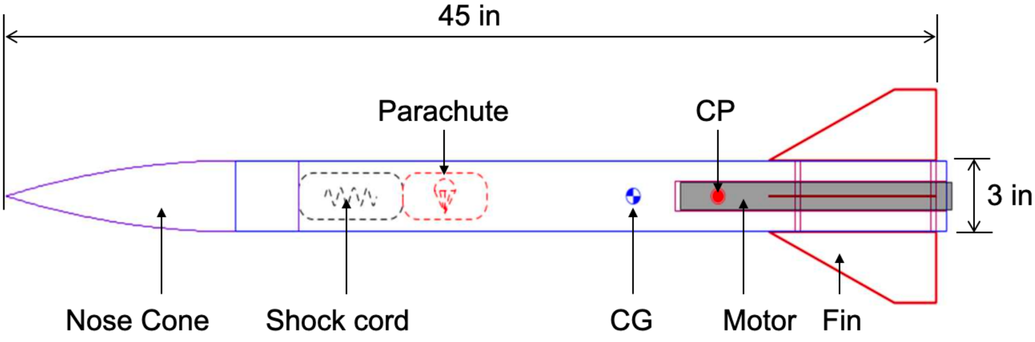


Fig. 1 *2D model rocket*

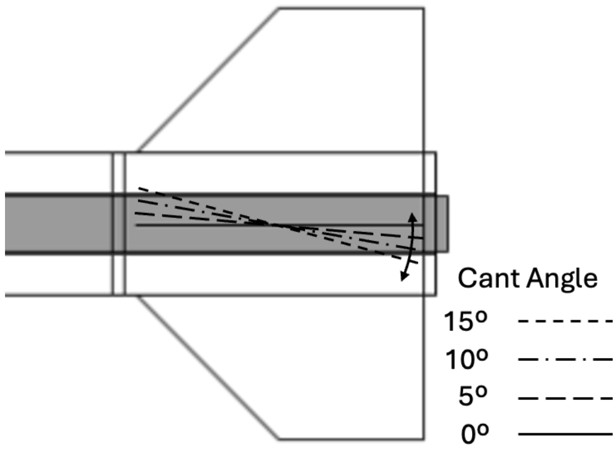


Fig. 2 *Definition of fin's Cant Angle*

2.2 Fin Design

The design of the rocket fin is shown in Fig. 3. This study selected the Clipped Delta Fin design as it is one of the most used in experimental rockets [11]. The Clipped Delta Fin is like a parallelogram, with the fin swept to the rear and the root and chord lines nearly parallel. These kinds of fins are primarily utilised in high-performance rockets to achieve low drag forces [12]. The clipped design reduces the overall surface area at the fin tips, streamlining the fins and minimising air resistance during the rocket's ascent. This design balances stability and drag reduction, enhancing the rocket's speed and overall efficiency. In aerodynamics, the optimum angle of attack is typically around 3° to 5° and the maximum cant angle that can be set in the Open Rocket is 15°. In addition, a cant angle larger than 15° may exceed the critical angle of attack and cause the fins to stall. Hence, the chosen cant angles for this study are 0°, 1°, 2°, 3°, 4°, 5°, 10°, and 15°.

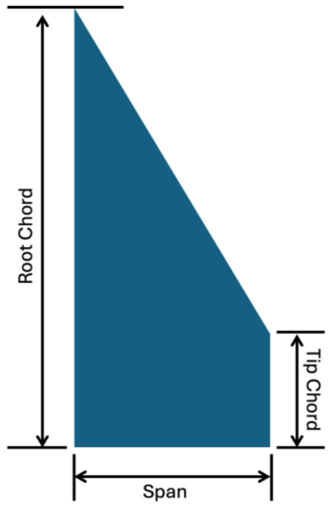


Fig. 3. *Clipped Delta Fin [11]*

Table 1 *Clipped Delta fin configurations*

Parameter	Configuration
Number of fins	4
Root chord (in)	6
Tip chord (in)	3
Span (in)	3
Sweep length (in)	3
Sweep angle (°)	45

2.3 Motor Specification

In this study, the selected motor for this rocket model is H125W manufactured by AeroTech. A lot of motors are available in the Open Rocket library. However, the H125W is chosen because it is suitable for the rocket model and the size of the motor fits perfectly in the inner tube. Furthermore, the motor is in H class, which falls into the high-powered motor category. This categorises the rocket as a high-power rocket. Table 2 shows the H125W motor's specification while Table 3 lists the rocket performance using this motor. The rocket with H125W is expected to achieve apogee at 2883 m altitude within 12.8 s.

Table 2 *H125W motor specifications*

Avg. Thrust (N)	Burn Time (s)	Total Impulse (Ns)	Thrust to Weight	Max Thrust (N)	Motor Weight (g)	Size (mm)
122	2.58	317	7.32:1	276	188	29/330

Table 3 *Rocket performance*

Altitude (ft)	Flight Time (s)	Time to Apogee (s)	Velocity off Pad (ft/s)	Max Velocity (ft/s)	Velocity at Deployment (ft/s)	Landing Velocity (ft/s)
2883	138	12.8	74.2	484	1.02	22.8

2.4 Launch Condition

Prior to simulating the rocket flight, launch conditions define a number of parameters, including wind direction, turbulence intensity, and average wind speed. The launch conditions for all model rockets are the same in this study because the rockets are launched from the same place. The conditions, as shown in Fig. 4, specify an average wind speed and standard deviation of 0 mph, with a turbulence intensity of 0% to prevent the effect of any wind disturbances. The temperature is set at 28°C, as this study assumes normal temperature and pressure at 1 atm.

The selected launch site is situated in Parit Raja, Johor, with longitude, latitude, and altitude coordinates are 1.86°N, 103°E, and 23.3 ft, respectively.

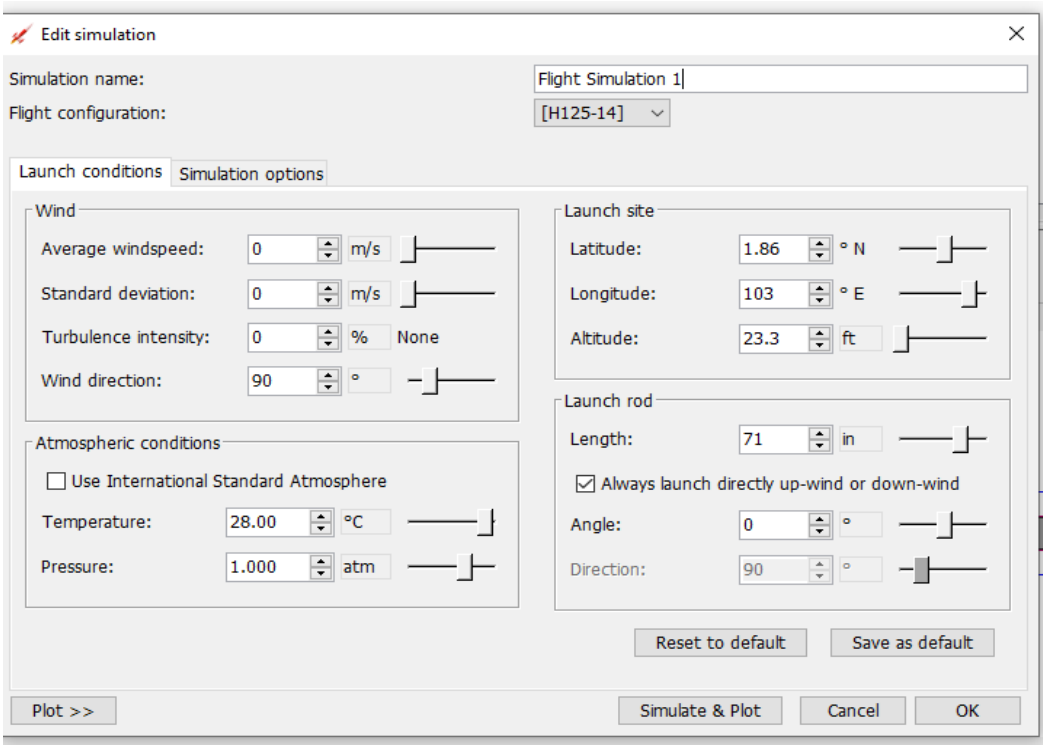


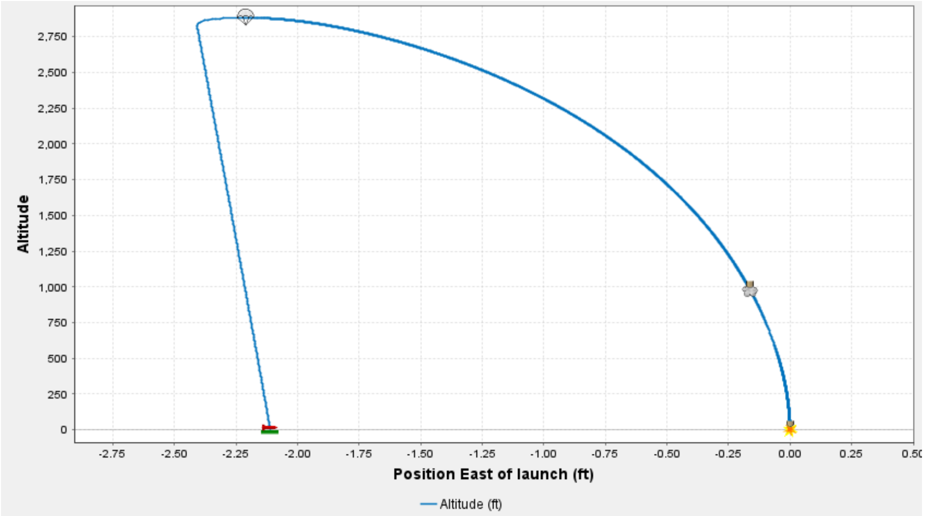
Fig. 4 *Launch conditions for all model rockets*

3. Result and Discussion

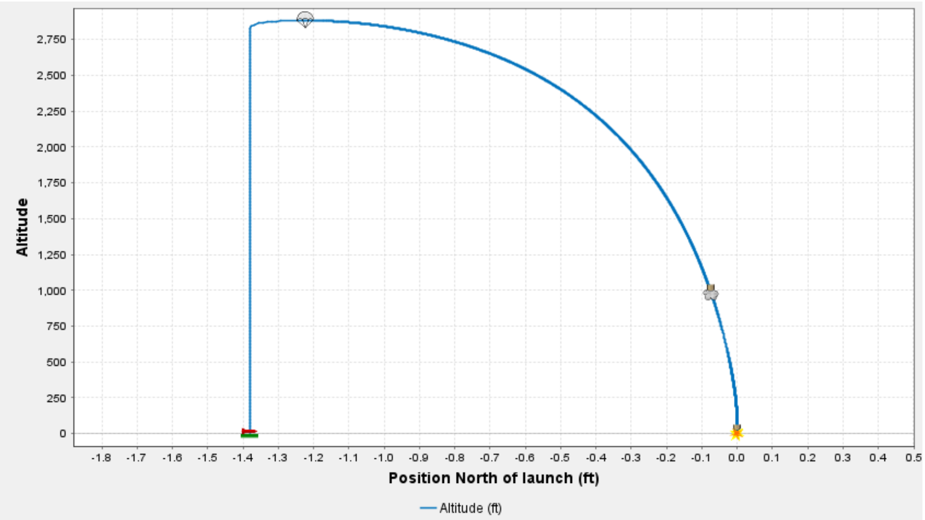
This section explains the results obtained from Open Rocket simulations. In this study, the trajectory and aerodynamic characteristics of model rockets with different cant angles—0°, 1°, 2°, 3°, 4°, 5°, 10°, and 15°—are investigated.

3.1 Rocket Trajectory

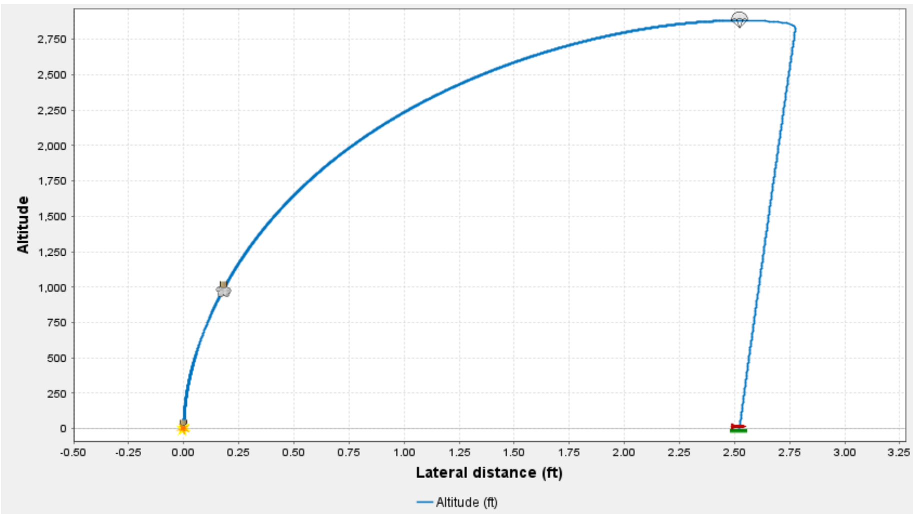
The trajectory simulation results offer a comprehensive view of each model rocket's trajectory in both the vertical and horizontal dimensions. The initial phase of the graph captures the ascent of the model rockets from the launch site, showcasing how altitude increases with horizontal or ground distance. Analysing the correlation between altitude and ground distance provides insights into how changes in altitude correspond to lateral manoeuvres. Furthermore, lateral distance can be defined as the shortest ground distance of the rocket's apogee from the launch site.



(a)



(b)



(c)

Fig. 5 *Altitude vs. (a) Position east of launch; (b) Position north of launch; (c) Lateral distance*

Each model is subjected to three different simulations' results to analyse the trajectory characteristics. First, "Altitude (ft) vs. Position East Launch (ft)" as shown in Fig. 5 (a) where the graph explores the relationship between altitude and the rockets' eastward direction. Next, the "Altitude (ft) vs. Position North Launch (ft)" simulation as shown in Fig. 5 (b) explores the relationship between altitude and the rocket's northward position. Finally, the "Altitude (ft) vs. Lateral Distance (ft)" simulation shown in Fig. 5 (c) investigates the connection between the rocket's lateral distance travelled and altitude.

In the context of rocketry, "Position East of Launch" describes the horizontal distance the rocket moves eastward, whereas "Position North of Launch" refers to the horizontal distance it travels northward from the launch site. In addition, the rocket's horizontal apogee distance in the eastward and northward directions for each cant angle is concluded in Table 4. These results are essential to demonstrate how the rocket moves across the ground as it ascends into the sky.

Table 4 shows that the maximum altitude is slightly decreasing as the cant angle increases. At small cant angle from 0° to 3°, the rocket reached approximately 2883 ft altitude and then decreased until 2876 ft altitude at 15° cant angles. The table also indicates that all simulated rockets had horizontal apogee distances in negative values for the rest of the cant angles. The negative value of the Horizontal Apogee Distance for the East-West axis indicates a westward direction, while for the North-South axis, it indicates a southward direction. For the simulation of altitude versus "Position East of Launch", the horizontal distance from the launch site to the apogee decreased as the cant angle increased. For instance, the distance was -3.12 ft for a 0° cant angle and -0.93 ft for a 15° cant angle, indicating a westward trajectory.

Table 4 *Maximum altitude, horizontal apogee distance and lateral distance for different cant angle*

Cant Angle (°)	Max Altitude (ft)	Horizontal Apogee Distance in East-West axis (ft)	Horizontal Apogee Distance in North-South axis (ft)	Lateral Distance (ft)
0	2883	-3.12	0.00011	3.06
1	2883	-3.02	-0.38	3.04
2	2883	-2.89	-0.72	2.97
3	2883	-2.65	-0.93	2.82
4	2882	-2.44	-1.11	2.68
5	2882	-2.21	-1.22	2.52
10	2880	-1.37	-1.29	1.88
15	2876	-0.93	-1.11	1.45

The horizontal distance from the launch site to the apogee increased in the southward direction as the cant angle increased. As listed in Table 4, it was approximately 0.00011 ft to the north for a 0° cant angle and shifted southward for 1° to 15° cant angle, ranging from 0.38 ft to 1.11 ft to the south.

The lateral distance in Table 4 combines the east-west and north-south distance to show the distance to reach apogee from the launch site. The lateral distance for the rocket decreases from 3.06 ft for 0° cant angle to 1.45 ft for 15° cant angle. The changes in lateral distances are not linear. As shown by Fig. 6, the rate of change varies. At small cant angles, such as from 0° to 2°, the rate of change in lateral distances is small. However, as the cant angle increases, the rate of change in lateral distance increases from 3° until 10° cant angle and slightly decreases again until 15° cant angle.

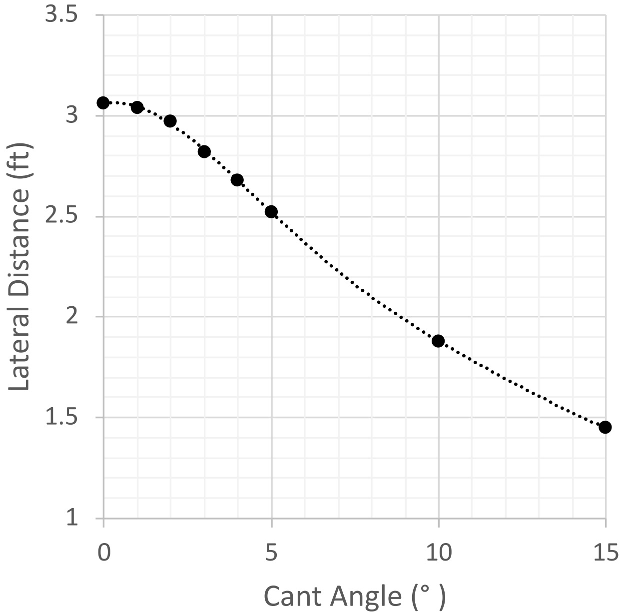


Fig. 6 *Changes of rocket lateral distance with different cant angle*

3.2 Stability and Aerodynamic Drag of the Rocket

The stability margin results serve as a comprehensive exploration of the dynamic stability exhibited by each model rocket throughout its entire flight. Additionally, the aerodynamic drag results display the maximum drag force on the rocket at specific time. The study simultaneously reveals the aerodynamic characteristics of model rockets through these two important results.

The stability is represented in the calibres (cal) unit, where a calibre is the maximum tube diameter of the rocket [13]. Based on the data in Table 5, it is shown that the values of maximum stability when the motor burnt out are the same for each rocket with different cant angles. The time taken for the motor to burn out is the same, at 2.77 seconds. However, the value of the maximum stability for each model rocket when the motor burnt out is constant at 2 cal for 0° - 5° cant angle but slightly increasing as the cant angle becomes larger.

Table 5 *Maximum stability, motor burnout time, max drag force, time to max drag force for different cant angle*

Cant angle (°)	Max stability (cal)	Motor burns out time (s)	Max Drag Force (N)	Time to Max Drag Force (s)
0	2.00	2.77	29.13	2.03
1	2.00	2.77	29.13	2.03
2	2.00	2.77	29.13	2.03
3	2.00	2.77	29.13	2.03
4	2.00	2.77	29.13	2.03
5	2.00	2.77	29.13	2.03
10	2.02	2.77	29.12	2.03
15	2.04	2.77	29.10	2.03

The simulation results of max drag force provide a comprehensive exploration of how aerodynamic forces, specifically drag, influence the trajectory of each model rocket throughout its entire flight. Drag force is one of the factors that affect the interaction of the rocket with the surrounding air, impacting its acceleration, stability, and descent. This analysis explores the dynamic changes in drag force over time, offering crucial insights into the aerodynamic performance of each model rocket. The result will highlight key moments such as initial ascent, maximum drag force, post-burnout dynamics, and parachute deployment.

In Table 5, only the maximum drag force of the rockets and the time taken for the rockets to reach the maximum drag force are presented. The time taken for each model rocket to reach the maximum drag force is the same, at 2.03 seconds, and the value of the maximum drag force for each model rocket is also the same, at 29.13 N, but slightly different with 10° and 15° cant angles, which are 29.12 N and 29.10 N, respectively. This indicates that the maximum drag force is slightly decreasing as the cant angle becomes larger.

4. Conclusion

This study aimed to investigate the effect of different cant angles of fins on the trajectory and aerodynamic characteristics of model rockets. The trajectory characteristics were evaluated through simulations of altitude versus position east of launch, altitude versus position north of launch, and altitude versus lateral distance. Meanwhile, the aerodynamic characteristics were evaluated through simulations of stability margin versus time and drag force versus time.

In conclusion, different fin cant angles slightly alter the trajectory characteristic of model rockets. Higher cant angles resulted in shorter horizontal and lateral distances from the launch site to the apogee, suggesting a more vertical trajectory. Furthermore, the overall stability and aerodynamic drag characteristic did not significantly impact by the different fin cant angle. The changes in stability and drag become apparent at large cant angle.

Overall, the findings provided valuable insights into the design and optimization of model rockets for various flight conditions although this project even though this study was restricted to adjusting fin cant angles from 0° to 15° due to the constraint of the Open Rocket software.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm their contribution to this manuscript as follows. ***Study conception and design:*** *Nicholas Bawing Jampi and Mohd Fadhli Zulkafli.* ***Data collection:*** *Nicholas Bawing Jampi.* ***Analysis and interpretation of results, and manuscript preparation****: Nicholas Bawing Jampi and Mohd Fadhli Zulkafli. All authors reviewed the results and approved the final version of the manuscript.*

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