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Mathematical and Computational Fluid Dynamic (CFD) Analysis of a Low Altitude Rocket Stability for Varying Fin Root Chord

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ABSTRACT

One of the major components in determining the stability of a model rocket is the rocket fin. In order to define the static stability of the model rocket, the relative positions of the centre of gravity and centre of pressure (CP) needs to be calculated first. The centre of gravity depends on the mass distribution of the rocket meanwhile the centre of pressure analysis requires the pressure distribution over the surface of the rocket body. This induces a much more challenging problem as in order to obtain the pressure distribution, wind tunnel testing is required. This present study aims to analyze the centre of pressure of model rocket using mathematical equations as well as computational fluid dynamics (CFD) with varying fins root chord. Mathematical prediction using theoretical Barrowman's equation as well as OpenRocket software and CFD are used to obtain the centre of pressure as well as the static stability of the designed model rocket. Wind tunnel testing is not necessary as CFD analysis is able to provide the centre of pressure of the rocket. The data from all approaches was then compared and analyzed. It is found that the centre of pressure results from the theoretical Barrowman's equation and CFD shows the same trend of linear increase in CP as the root chord increases. The stability obtained from the Barrowman's equation ranging between 3.0 to 3.4 cal and OpenRocket at 2.91 to 3.27 cal shows percentage error of less than 5%. It is also found that the stability of the rocket using CFD analysis shows unstable rocket with stability range of 0.45 to 0.55 cal.

Keywords: Rocket stability; Barrowman's equation; centre of pressure; centre of gravity; CFD analysis.

INTRODUCTION

A rocket is known as a system that attempts to maintain its movement and change altitude when wind hits the rocket body (Hari Prasanna Manimaran et al. 2020). The applications of rockets vary from education, weaponry to space exploration. It is deemed critical to test the stability of rocket before launching to prevent any casualties from happening. Stability is defined as an object's ability to return to its original condition or state after being disrupted (Hansson & Helgesson 2003). In a rocket context, it refers to the rocket's ability to maintain its movement while in flight without wobbling or tumbling. The body is said to be unstable if it moves from its initial position after being perturbed (Zhang et al. 2016). The basic rule that must be followed when designing a stable rocket is the position and distance between the pressure and gravity centers (Heeg et al. 2020).

Qiao et al. (2023) stated in his "Calculating the Centre Pressure of a Rocket" that the static stability criterion can be achieved when the centre of gravity remains above the centre of pressure. The centre of gravity of a rocket is located where the entire weight of the rocket is concentrated (Balance point). Finding the centre of gravity of a rocket can be quite simple by doing a balance check (Qiao et al. 2023). The balancing check can be done by tying some string around the point of centre of gravity of the rocket where the rocket stays level. The point at which aerodynamic forces are concentrated on the rocket can be defined as the centre of pressure (Krishnarao et al. 2017). The centre of pressure is a little different from the centre of gravity because it only occurs when there is air moving around the rocket. To find the centre of pressure of a rocket is more difficult because it can only be done during the rocket flight in the atmosphere. There are four forces that contribute during rocket launching into the atmosphere which are weight, thrust, lift, and drag (Ogale et al. 2011). The weight forces are gravitational forces that act through the centre of gravity while the thrust force is the force that contributes in moving the rocket forward. These two forces are acting through the centre of gravity. The lift forces that control the motion of the rocket and the drag forces that act in parallel to the wind are the aerodynamic forces that act on the centre of pressure (Kumar & Nayana 2016).

Most smaller rockets with simpler designs and lower target altitude below the Karman line utilize fins to provide stability of the rocket (Dallas et al. 2020). The function of fins on a rocket is to move the centre of pressure behind the centre of gravity (Américo et al. 2020). It is important to identify the optimum parameters for fins on a rocket because adding fins will generate more drag force and reduce potential altitude (Solomon, 2020). The stability of a rocket can be affected by the number of rocket fins. Usually, many small rockets use between 3 and 4 fins to provide enough stability. For the larger rocket, they used thrust vector control as a system to maintain and control the rocket altitude during powered flight (Ensworth, 2013). The surface area and aspect ratio of the fin are two of the most crucial aspects of the fin's geometry. When a fin has a larger surface area, resistance increases. In a study of Brazilian sounding rockets, researchers found that the surface area of the fins has a bigger effect on drag and performance than fin planform shape (Barbosa & Guimãraes 2012). The fin aspect ratio is related to surface area because it is calculated by dividing the square of the fin's semi-span by its total surface area. In terms of aerodynamic efficiency, greater aspect ratios outperform lower aspect ratios (Srivastava & Thakur 2022).

Barrowman's equation outlines a method in determining the stability of a model rocket using the centre of gravity and centre of pressure of the rocket (Galejs, 2009). The stability of a rocket is important for the preliminary design calculations before the fabricating process of the rocket. The main key assumptions made by Jim Barrowman for the Barrowman's equation includes a slender body, where the length of the rocket should be greater than its diameter. The equation also neglect the effects of fins which is a very important influence of a rocket stability. In addition to that, the air flow around the rocket is assumed to be incompressible which is only a reasonable for a low-speed flight but not valid fro high-speed flight at high altitude.

The previous study about Smokey SAM Rocket was conducted to observe the flow behavior of the rocket's prototype (Abdullah et al. 2021). The computational fluid dynamics (CFD) method is utilized in this study in order to conduct an analysis that evaluates the aerodynamic performance of the Smokey Sam prototype rocket design. At high-speed trajectory operation, it was determined that an exact pressure distribution was necessary for the best rocket material to maintain the best strength to weight ratio at high pressures (Hussein et al. 2022). The CFD simulation of this study can be concluded as a success since the results are converged. Because the fins act as a stabilizer for the rocket while in mid-air, it has been shown that they contribute significantly more to the aerodynamic load than the body (Zhu et al. 2018).

In summary, the rocket was subjected to a variety of forces and disturbances throughout the flight. The stability aspect must be defined in order to recover and preserve the rocket. The stability of a rocket is determined or depends on the location of the rocket's centre gravity and centre pressure. Open Rocket software, which is based on the Barrowman equation is used by the majority of amateur rocketeers to predict the stability of the rocket (Abni et al. 2023). As far as the authors are aware, there has not been much work done to validate the software especially the prediction of the centre of pressure. Therefore, this study uses CFD to predict the centre pressure of clipped delta fins of varying root chords.

METHODOLOGY

In order to determine the centre of pressure of a rocket with varying root chord, a computational approach using OpenFoam is used. The design used is clipped delta fins and are kept constants for all approaches. As the root chords varied, the sweep length of the rocket was also varied as the trailing edge of the fin is always perpendicular to the body of the rocket. The rocket body has a diameter of 16 cm. The fin root chord was varied from 16, 18, 21, 23, 25 and 27 cm.

Firstly, the centre of pressure is calculated using the theoretical equation of Barrowman, which are presented in detail in the following section. The equations were calculated using the equation as well as using open-source software OpenRocket. Next, prediction of the centre of pressure was done by solving the Navier-Stokes and continuity equation using computational fluid dynamics simulations. A 3D representation of the rocket was modelled using computer-aided design (CAD) software, which was meshed and analyzed using OpenFoam computational fluid dynamics. The mathematical predictions for estimation of the centre of pressure of rocket are shown in the following section.

ESTIMATION OF CENTRE OF PRESSURE USING BARROWMAN'S EQUATION

The location of the centre of pressure for a given rocket geometry was estimated using Barrowman's Equation. The components of the equation are broken down into 4 parts which are the centre of pressure for the nosecone, conical shoulder, conical boattail, and fins of the rocket. Equation (1) was used to calculate the centre of pressure of the rocket. As the rocket in the present study does not contain a conical shoulder and boattail, Equation (1) reduce to Equation (2).

$$\bar{X} = \frac{(C_N)_n\bar{X}_n + (C_N)_{cs}\bar{X}_{cs} + (C_N)_{cb}\bar{X}_{cb} + (C_N)_f\bar{X}_f}{C_N} \quad (1)$$

$$\bar{X} = \frac{(C_N)_n\bar{X}_n + (C_N)_f\bar{X}_f}{C_N} \quad (2)$$

The subscripts *n, cs, cb* and *f* represent each component of the nosecone, conical shoulder, conical boattail, and fins respectively. While $(C_N)_n$ represents the coefficient for the force on the nosecone, $\bar{X}_n$ represents the length between the centre of pressure of nosecone with the tip of nosecone. The same subscripts were used for the other components that contribute to the estimation of the centre of pressure for the whole rocket. The geometrical of the rocket design used in this study are presented in Figure 1.

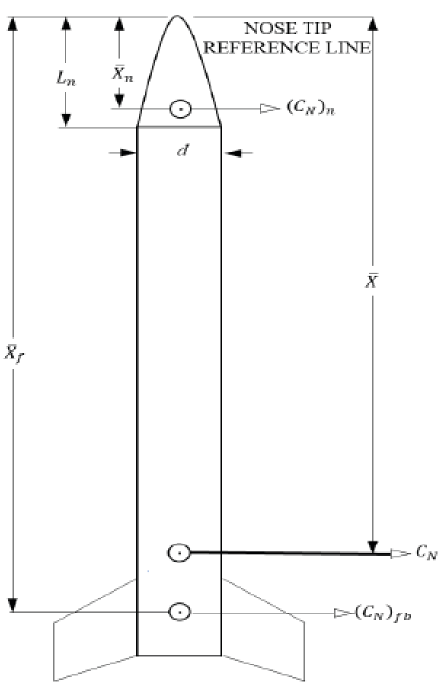

FIGURE 1. Geometrical definitions of the designed rocket

The normal force coefficient for the nosecone, $(C_N)_n$ is equal to 2 for all nosecone shapes. Meanwhile, the location for the centre of pressure of each nosecone shape is different accordingly. This study used ellipsoidal shaped nosecone where the location of the centre of pressure is given in Equation (3), where L_n refers to the length of the nosecone which is 40cm.

$$X_n = 0.333L_n \quad (3)$$

Figure 2 represents the generalized fin shape that was used in this study called clipped-delta fins. The force on the fins with n number of fins was calculated using Equation (4), where n is the number of fins used on the rocket which is 4. The subscripts S, l, a and b refers to the semispan of the fins, the length of the mid-chord line, the fin root chord, C_R, and the tip chord, C_T, respectively. The interference factor for the airflow between the connection of the fins and the rocket body is taken into account as it causes a slight disturbance in the airflow around the rocket body. The interference factor around the fin-body is known as K_{fb} is given in Equation (5), where R is the radius of the body between the fins.

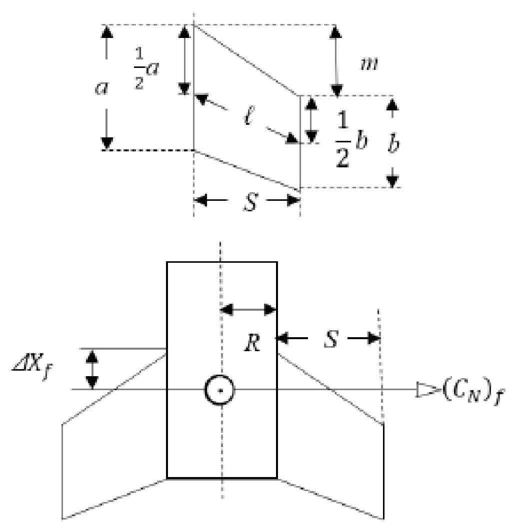

FIGURE 2. Geometrical definitions of a typical rocket fins

The fins centre of pressure location is not affected by the number of fins as all the fins are in the same clipped-delta shape and size. The location is calculated using Equation (6) where X_r is the distance between the tip of nosecone to the front edge of the fin root.

$$\bar{X}_f = X_r + \frac{m}{3}\frac{(a+2b)}{(a+b)} + \frac{1}{6}\left[(a+b) - \frac{ab}{a+b}\right] \quad (6)$$

Finally, the total force on the entire rocket is given by the summation of each force on the separate components contributing to the centre of pressure location of the rocket. After the reduction of conical shoulder and boattail components, the equation is reduced to Equation (7).

$$C_N = (C_N)_n + (C_N)_f \tag{7}$$

Results from Equation (1) were obtained from both theoretical calculations using Excel as well as an open-source software known as OpenRocket. Aside from giving greater functionality and feedback of a real time performance, OpenRocket is also able to evaluate other flight performance such as the drag and thrust produced throughout the flight simulation. Before the analysis inside the OpenRocket software was done, the properties such as the density of the materials desired were obtained. The positions of the centre of pressure and gravity change as the materials incorporated also change.

In order to calculate the stability of the rocket, both the location of the centre of gravity and centre of pressure were needed (Rohini et al. 2022). The results of centre of gravity are obtained from the OpenRocket software, meanwhile the stability of the rocket is calculated using static margin where the distance between the centre of gravity and centre of pressure is divided by the diameter of the rocket as in Equation (8).

$$M_e = \frac{\bar{X}_P - \bar{X}_G}{d} \tag{8}$$

3D MODELLING

CAD software was utilized to model a 3D representation of the model rocket designed. Figure 3 represents a 3D model of the rocket used in this study. 4 clipped-delta fins with a semispan of 25 cm and tip chord of 16 cm was designed. The shape of the nosecone was set to be ellipsoidal with a length of 40 cm and diameter of 16 cm. Manipulated variables selected were the root chord of the fins. The root chord varies between 16, 18, 21, 23, 25 and 27 cm.

The pressure distribution around the whole rocket using computational fluid dynamics software was integrated in order to obtain the centre of pressure of the rocket as in Equation (8) where $C_{P,x}$ refers to the longitudinal centre of pressure of the rocket, x is the longitudinal location and $p(x)$ is the local pressure.

$$C_{P,x} = \frac{\int x p(x) dx}{\int p(x) dx} \tag{8}$$

In the area near the physical surfaces of the rocket, a high-resolution meshing configuration was constructed to obtain any expected strong velocity gradient during the analysis. The inlet plane was set to a streamwise velocity of 300 m/s while the temperature and pressure were set is at ambient values of 305 K (32℃) and 100 kPa respectively. In order to allow for a fully developed flows, the simulations were conducted for a reasonable duration of time and the centre of pressures were also calculated while excluding the transient part of the simulation data.

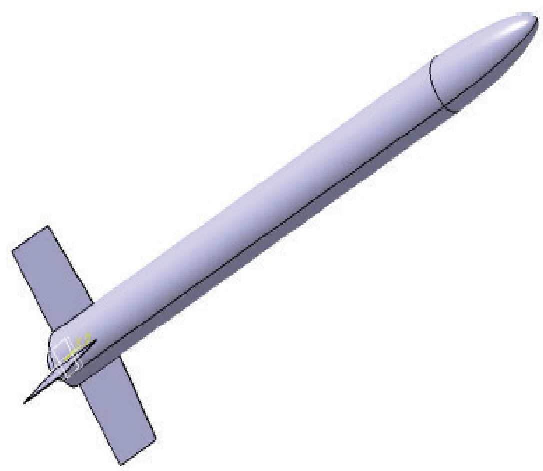

FIGURE 3. 3D representation of a rocket analyzed in the study

RESULTS AND DISCUSSION

MATHEMATICAL ANALYSIS (BARROWMAN'S EQUATION)

The results from analytical calculation and OpenRocket analysis are shown in Table 1 and Table 2 while Figure 4 represents the graph of stability against the root chord length.

It is found from the mathematical analysis that as the root chord length increases, both the location of centre of gravity and centre of pressure moves further from the nosecone and closer to the fins. As the length of the root chord increases, it increases the surface area of the fins thus increasing the volume on the fin. As the volume of the fin increases, the mass of the rocket also increases at the back thus moving the centre of gravity towards the fins of the rocket (Shahir & Sapit, 2021). Both mathematical analyses using the Barrowman's equation show the same trend of linear increase in stability as the root chord length increases. OpenRocket simulation shows a slightly lower results where the highest stability is at 3.27 cal while Excel calculation provides higher stability at 27 cm root chord of 3.42 cal.

TABLE 1. Centre of pressure and stability using theoretical analysis

Root chord (cm)	Centre of gravity (cm)	Centre of pressure (cm)		Percentage Error (%)
		Excel	OpenRocket	
16	125	173.61	175	0.795
18	126	175.47	175	0.268
21	127	178.08	176	1.180
23	127	179.71	176	2.110
25	128	181.28	177	2.418
27	128	182.79	177	3.270

TABLE 2. Centre of pressure and stability using theoretical analysis

Root chord (cm)	Centre of gravity (cm)	Stability (cal)		Percentage Error (%)
		Excel	OpenRocket	
16	125	3.04	2.91	4.400
18	126	3.09	2.98	3.753
21	127	3.19	3.05	4.665
23	127	3.29	3.11	5.934
25	128	3.33	3.21	3.739
27	128	3.42	3.27	4.718

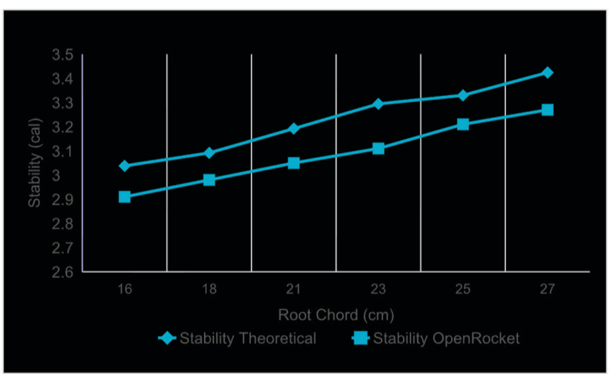

FIGURE 4. Stability plotted against the root chord length

It is seen that the percentage error varies between 0.268% and 3.270% for the centre of pressure. Both Barrowman's equation and OpenRocket analysis are able to obtain similar trends in the error which concludes the comparable accuracy as the percentage error is less than 5%. The results of percentage error from stability analysis also shows comparable results as the percentage error ranges from 3.739% to 5.934% without a clear trend. This suggests that the accuracy of the stability is not directly related to the fin root chord of the rocket.

The slight difference in the results is due to the other components taken into consideration by OpenRocket while Barrowman's equation only takes into account the dimensions of the designed rocket as well as the shape of the nosecone. OpenRocket takes into consideration the mass distribution for each component on the rocket while the Barrowman's equation neglects the effect of fins such as the shape and material used. Meanwhile OpenRocket has taken into consideration the effect of drag produced by each material used for the components. Therefore, the results from OpenRocket are more reliable compared to the Excel calculation.

COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSIS

Table 3 shows the data from computational fluid dynamics analysis using the OpenFoam software. Figure 5 and Figure 6 show the graphs plotted for centre of pressure and stability against the root chord length for the mathematical analysis and CFD analysis. It is noted that the stability calculated for the CFD analysis is derived using Equation (8) and the centre of gravity is obtained from OpenRocket analysis.

TABLE 3. OpenFoam software data from CFD analysis

Root chord (cm)	Centre of pressure (cm)	Stability (cal)
16	132.292	0.456
18	133.199	0.449
21	134.452	0.466
23	135.245	0.515
25	136.011	0.501
27	136.721	0.545

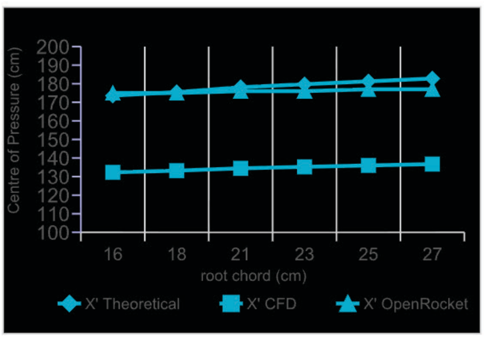

FIGURE 5. Location of centre of pressure plotted against the root chord length

It is observed that the trend of stability coincides with the trend of the location of centre of pressure for varying root chord length. As the length increases, both mathematical and CFD analysis shows that the location of centre of pressure moves further away from the tip of the nosecone. The highest stability obtained from the CFD analysis is only at 0.545 cal where it is considered unstable. The range for a stable rocket should be within the range of 1 to 2. Other modifications need to be done in order to increase the stability of the rocket to achieve a stable flight. The CFD analysis also shows a slight fluctuating data for the stability instead of linearly increasing data from mathematical analysis.

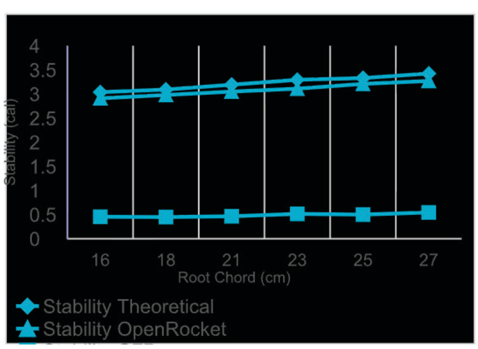

FIGURE 6. Graph of stability against root chord length

The result from the CFD analysis shows a much lower value for both centre of pressure and stability in comparison to the mathematical analysis. The discrepancy in the results is due to the assumptions made by Barrowman during the equation derivation. Barrowman's equation assumes that the airflow over the rocket is smooth and does not change rapidly throughout the flight. The CFD analysis on the other hand takes into consideration the effect of interference over the airflow between the rocket body and the fins. This results in a much lower value of centre of pressure as well as the stability. Other assumption made during the derivation of Barrowman's equation is that the speed of rocket should be less than the speed of sound (180 m/s) while the boundary condition in OpenFoam software is at 300 m/s. The discrepancies also show how the analysis of airflow interactions play an important role in the analysis of stability for the rocket.

CONCLUSION

As this study aims to analyze the centre of pressure as well as the stability of model rocket using mathematical analysis and computational fluid dynamics analysis, the results from each analysis was compared. It can be concluded that as the root chord length of the fins increases from 16 cm to 27 cm, the centre of pressure moves further away by 5.5% from the nosecone thus improving the stability from 3.04 to 3.42 cal. This results in changes in the stability as well since the stability of the rocket coincides with the location of the centre of pressure of the rocket. It is also found that the CFD and mathematical predictions differ due to assumptions made in Barrowman's equation. However, the CFD result validates the mathematical prediction of how the root chord length affects the stability of the rocket although with a much lower stability at 0.545 cal. Given the results, it is recommended that a fin root chord length of 27 cm offers the best overall stability based on the mathematical model, though further modifications are required to improve stability in real-world conditions as per CFD analysis. Despite the validation, the discrepancy calls for additional scrutiny or even adjustments to the Barrowman equation.

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DECLARATION OF COMPETING INTEREST

None.

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