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Design Analysis of Rocket Tail Fins Aimed at Higher Apogee by Computer Simulation

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Justyn is an undergraduate student at the University of Maryland, Baltimore County, currently working to obtain a bachelor's degree in Mechanical Engineering. After completing his undergraduate studies, Justyn looks to pursue higher education and obtain a Ph.D. in Aerospace Engineering.

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Mr. Marc Caballes was born and raised in Bogo City, Philippines. He arrived here in America last 2009. As a kid, every time his Mom asked him to do something, he always looked for the most efficient approach to get the job done. Thus, it is no surprise that he is currently pursuing a doctorate in Systems Engineering at Morgan State University (MSU), where his Professors help him enhance his capabilities in looking for the most optimal solution while delivering quality results. Some people might say that it is okay to make mistakes as long as you learn from them. However, Mr. Caballes beg to differ. For him, it is more convenient to eliminate that "mistake" before it happens. Hence, he always wants to have an outcome of a 99.9998% success rate (mistake-proof). Marc has extensive knowledge and experience in Additive Manufacturing (AM), 3D Modeling and Design, Design of Experiments (DOE), Systems and Reliability Engineering, Lean Practices and Techniques, and Process Simulations.

Aside from being a Professor in Robotics and Mechatronics Engineering Department at Baltimore City Community College (BCCC), Marc is the team lead in MSU's Liquid Propellant Rocket Subtask Team, where he reviews and designs the essential rocket components such as the nose cone and all the way to the rocket's boat tail. In addition, he is also responsible for leading diverse and highly motivated engineering students in the RockOn program, where they implement and test a rocket payload that can measure and record the acceleration, humidity, pressure, temperature, and radiation counts during flight. The payload system was launched on NASA's Terrier Improved-Orion Sounding Rocket at their flight facility in Wallops, Virginia, and was successfully recovered at the Atlantic Ocean. Marc made several presentations and publications in domestic and international conferences, including MDSGC, FTC, ASEE, SISE, ICTAA, INCOSE, and INFORMS. His maxim in life is, "Never confuse movement with progress. Because you can run in places and not get anywhere."

Miss Margaret Ajuwon, Morgan State University

Margaret Ajuwon is a doctoral student of Industrial Engineering at Morgan State University, Baltimore MD. She has a Master's degree in Industrial Engineer from Southern Illinois University, Edwardsville (SIUE). She also possesses a Bachelors's degree in Mathematics and has been using her analytical skills in the optimization of processes. She currently works as a graduate research assistant for the Morgan State University Rocketry Program.

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Design Analysis of Rocket Tail Fins Aimed at Higher Apogee by Computer Simulation

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Abstract: The Rocketry Team at Morgan State University is developing a single-stage liquid-propellant rocket (LPR) with a targeted apogee of 13,000 feet. Due to the complexity of the LPR, each component of the rocket must be studied to optimize parameters that play a role in achieving the design apogee. These parameters do so either directly or by affecting other parameters in the optimization space. A wide variety of research papers and peer-reviewed journals that deal with the rocket nose cone and the characteristics of its airframe are already publicly accessible. However, only a few in-depth studies specifically address the design of the rocket's tail fins. Thus, this paper focuses on how different factors, such as the planform shape of the fins – clipped delta and trapezoidal; fin materials – carbon fiber, aluminum, and fiberglass; and its geometric dimensions – root chord and sweep angle, will affect the estimated apogee of a rocket and what is an ideal combination of design parameters. The simulation results collected using the software OpenRocket Simulator shows the possible outcomes of the rocket's apogee. Furthermore, a factorial design methodology was employed using the collected data and the Minitab software to perform statistical analysis to determine the significant factors and generate surface and contour plots. From the data in the study, the best rocket tail fin design for apogee was determined to be three clipped delta-shaped tail fins made of fiberglass.

Keywords: Liquid-Propellant Rocket (LPR), Apogee, OpenRocket Simulator, Minitab, Design of Experiments (DOE), Rocket Fin

1. Introduction

Morgan State University has received a grant of about 1.6 million dollars from BASE 11, a nonprofit 501 c3 STEM company whose mission is to provide access and awareness to women and minorities to pursue and succeed in careers in the areas of the Next Frontier Industries such as Aerospace, Life Sciences, Cyber Security, Augmented Reality and Virtual Reality, Data Analytics, Technology education, Advanced Manufacturing, and Autonomous Systems. BASE 11 plans to achieve this goal with their Next Frontier hands-on programs and events, mentoring programs, and additional resources and experiences that allow students the opportunity to learn from trained professionals in their respective fields. This funding will aid Morgan State in creating an aerospace laboratory, aerospace and rocketry program, and a rocketry team. One of the first tasks given by BASE 11 was to develop a Liquid Propellant Rocket that can reach an apogee of 150,000 ft by the year 2022. Rockets are not a modern-day invention. The first rocket designs date back to the year 1232 in early China. During that time, the Chinese were using rockets to prevent the advancement of Mongolian troops during the Battle of Kai-Keng (Benson, 2014). The next documented milestone in rocketry came in 1926, when physics professor Robert Goddard launched the first-ever liquid propellant rocket in Worcester, Massachusetts (Neufeld, 2016). Goddard's invention would ultimately lay the groundwork for future high-altitude rocket launches and space exploration missions to occur, such as the V-2 rocket developed by the Germans during World War II (History.com Editors, 2009).

1.1 Geometrical Dimensions

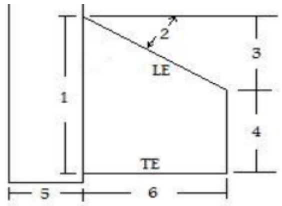

Figure 1. Parts of a Tail Fin

There are eight main terms when referring to the different nomenclature of a rocket tail fin. The diagram in Figure 1 labels those parts. The root chord, labeled as 1, is the length of the part of the tail fin that would integrate adjacent to the body of the rocket. The sweep angle, labeled as 2, is the angle between the leading edge, labeled as LE, and an imaginary line perpendicular to the root chord. The tip chord, labeled as 4, is the length of the tail fin that is parallel to the root chord. The semi-span, also known as the height of the tail fin, labeled as 6, is the perpendicular distance from the root chord to the tip chord. Lastly, the trailing edge, labeled as TE, is the length of the lowest part of the rocket tail fin.

1.2 Planform Shape

Tail fins are integrated into the tail end of the rocket to improve its overall stability. By attaching tail fins to the end of the rocket, its center of pressure, the point where the aerodynamic forces acting on the rocket are said to be concentrated, moves towards the rocket engine behind the center of gravity (Fraley, 2018). Doing so creates a torque force that will stabilize the effects of the perturbative forces that may alter the rocket's trajectory. The most effective method for moving the center of pressure towards the rocket's engine is to increase the surface area of the tail fin until the rocket's stability, measured using the caliber, the distance between the center of pressure (Cp) and the center of gravity (CG), becomes ideal. However, the increase in the tail fin's surface area will increase the drag force that the rocket experiences, potentially reducing the potential apogee the rocket can obtain (Barbosa & Guimarães, 2018). Likewise, an increase in the tail fin's surface area may result in overstability, which is when the distance between the Cp and the CG is too far apart, and the rocket will begin to tilt in the opposite direction of the strong headwind.

There are six main types of fin planform shapes, rectangular (a), swept (b), tapered swept (c), clipped delta (d), trapezoidal (e), and elliptical (f), as shown in figure 2. The rectangular fin is a tail fin whose surface looks like a rectangle. It is the most basic tail fin out of all the designs to manufacture. The swept tail fin has a design similar to the rectangular fin, except the sweep angle is greater than zero degrees. Both the swept fin and rectangular fin are not very aerodynamic. The tapered swept fin is a tail fin with a clipped delta fin design, except the leading edge and the trailing edge are not perpendicular to the body of the rocket. Instead, the leading and trailing edge are both at an angle between 90 degrees and 180 degrees away from the body of the rocket. This swept design lowers the center of pressure towards the end of the rocket away from the nose cone while being slightly aerodynamic due to its sweep angle at the leading edge allowing for less air to pass around the fin without making contact with it[fin], thus decreasing the drag force (Lucas, 2014). The clipped delta fin is a tail fin whose surface shape looks like a right triangle combined with a rectangle. This fin is used often in rocketry because of its manufacturability, and it is highly aerodynamic. Additionally, the trapezoidal tail fin has the surface shape of an isosceles trapezoid. The trapezoidal fin is also a commonly used tail fin because it is highly aerodynamic and easy to manufacture. However, unlike the clipped delta design, the trapezoidal design moves the center of pressure upwards towards the nose cone. Lastly, there is the elliptical tail fin. The elliptical tail fin, rather than having a straight edge at the tip chord, has a round elliptical shape. This planform-shaped tail fin is only used on rockets in which an elliptical shape is more optimal for the mission than the other planform shapes.

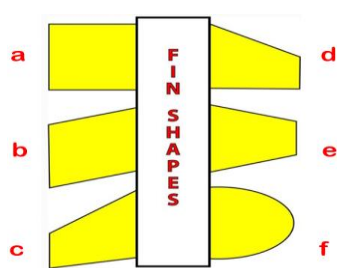

Figure 2. Planform Shape Designs

1.3 Materials

Selecting the appropriate material for the tail fins is dependent on the speeds that the rocket will reach. Lower speed rockets, such as small model rockets, manufacture their tail fins out of extremely lightweight materials because the dynamic forces acting on the rocket are significantly weaker than those of the larger model rockets. Rockets that achieve transonic speeds or faster might utilize tail fins made of durable, lightweight materials, composite materials, or a composite sandwich material due to the amplitude and frequency of aerodynamic forces the tail fins experience. The MSU liquid propellant rocket will need to reach speeds in the transonic regime to reach the targeted 13000 ft apogee. Therefore, potential options for the fin material based on previous designs are aluminum, carbon fiber, and fiberglass.

1.4 Problem Description and Objectives

The first step for building any vehicle for the first time is to establish the goals and minimum requirements for the vehicle, followed by researching and reading articles about the information other engineers have found from prior experiences contribute significantly to lowering the risks of failure. However, out of all the subsystems in a rocket, the number of articles on the rocket's tail fins and the design of the rocket's tail fins are limited to those such as *Multi-disciplinary multi-objective design optimization of sounding rocket fins* and *Multidisciplinary design optimization of sounding rocket fins shape using a tool called MDO-SONDA.* This lack of sources can make it challenging to generate the optimal rocket tail fins design. As stated earlier, the tail fins aim to improve the rocket's stability by moving the center of pressure away from the nose cone towards the tail end. One of the methods for accomplishing this is to increase the tail fins' surface area to achieve the desired stability. The trade-off of this method is the increase in the surface area will also increase the rocket's weight, thus requiring more fuel to reach the same apogee. Increasing the surface area also increases the forces of drag acting on the rocket, ultimately lowering the final apogee of the rocket (Priyadarshi et al., 2014). As a result, the problem of producing a tail fin design capable of maximizing the rocket's stability and minimizing its drag can be found.

This research aims to study how various factors such as the materials, geometrical dimensions, and planform shape design affect the rocket's performance in terms of apogee and stability using simulations. Furthermore, creating a 3D model of the rocket fin's optimal design will be needed to conduct a von-mises stress analysis once the ideal design factors, materials, shape, and geometrical dimensions are determined. With the recorded data, the final aim is to provide a general guideline for determining the design parameters of future tail fin designs.

2. Methodology

2.1 OpenRocket Simulations

OpenRocket is an open-source model rocket simulation software used to analyze rocket performance before building the intended design. The software makes it easy to determine which dimensions optimize the performance of the rocket. Since our overall goal is to reach 13,000 feet, apogee is an important factor when designing each component of this rocket. OpenRocket allows the user to simulate the expected apogee of the rocket using the dimensions and motor decided for the rocket. The simulation also provides max velocity, mass, max acceleration, and stability. When finalizing the design in the software, it displays the full assembly of the rocket, center of gravity, and the center of pressure. The rocket assembly includes the nose cone, the main and drogue parachutes, avionics bay, helium tank, propellants, engine, and fins. The rocket tail fins will then be modified throughout the parametric sweep to identify how to rank the factors that affect the rocket's stability and apogee. The factors considered are the different materials, planform shapes, and geometrical dimensions.

The results were obtained using a simulation in OpenRocket by varying parameters of the fins and making other components fixed. The height of the fin will be fixed in this experiment because only the effect of wave drag caused by the tail fin is considered. The effect of wave drag is only altered by changing the upstream and downstream sweep angles of the fin. The upstream and downstream sweep angles will be altered equally as necessary to create the desired planform geometry. Thus, the parameters of fins studied include material, chord length, sweep angles, and designs. The two sweep angles used will be 27.5 and 37.5 degrees because they are within the optimal sweep angle range of between 20 and 45 degrees (Minnesota & Stroick, 2011). The three root chord lengths used were 21.5, 31.5, and 41.5 inches. The table below summarizes the levels of each factor.

Table 1. Factors and Levels for the Simulation of the LPR

Factors	Levels		
Fin Design	Trapezoidal	Clipped Delta	
Sweep Angles	27.5	37.5	
Fin Material	Aluminum	Carbon fiber	Fiberglass
Root chord Length	21.5	31.5	41.5
Height	6.5		

2.2 SolidWorks 3D Modeling Software

The SolidWorks 3D Modeling Software is a tool for engineers and analysts to simulate gas and liquid flow in real-world conditions, analyzing the effects of heat transfer, fluid flow, and related forces on the immersed components. These effects are crucial to the preliminary design process, making it a valuable tool for any project. The software's Finite Element Analysis (FEA) tool can also be used to simulate fictitious conditions for the user to understand the durability of their design. As a result, the user can create the best design to ensure their product is at peak performance. In this study, the software was used for observing the von-mises stress analysis of the rocket fin. The von-mises stress(σ_v) is the equivalent stress value that determines if a material yields or fractures under a given stress based on the distortion energy theory (Dey, 2021). The von-mises stress can be calculated using the principal stresses($\sigma_{1,2,3}$) experienced throughout the material. The principal stresses are then used in equation (1).

$$\sigma_v = \sqrt{\frac{1}{2}((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)} \quad (1)$$

The material, any restraints the design may experience, and the total force acting on the preliminary design must be known for the software's FEA tool to calculate the von-mises stress. For this project, the material used will be the material that results in the highest apogee, the restraints were placed along the surface of the root chord that is fixed to the surface of the rocket, and the total force acting on the fins was the force due to wind resistance, or wave drag, which was calculated using equation (2).

$$F_D = \frac{1}{2}\rho v^2 A_c C_d \quad (2)$$

Where ρ is the density of air which was assumed to be 0.074 $\frac{lb}{ft^3}$ based on the given air conditions in the area around Morgan State University at the time of the simulations, v is the maximum velocity reached during the OpenRocket simulations, A_c is the cross-sectional area of the surface that is orthogonal to the airflow, and C_d is the average drag coefficient the tail fin experienced, based on the multiple Mach numbers the rocket reaches during flight, which was calculated to be 0.75. This FEA tool will provide helpful insight into the stiffness and failure strength of the fin during processing operations which can be used to determine if the tail fin will fracture during flight.

2.3 Design of Experiments using Minitab

Minitab is a data analysis software tool that allows the user to determine if a parameter is statistically significant by determining the p-value of the data to quantify each parameters' significance to the apogee. This software was used on this project to rank the multiple parameters when designing each sub-component of the rocket. Identifying which parameters make the largest impact in terms of apogee is extremely useful. Design of Experiments (DOE) is a tool used in various disciplines by engineers and scientists for product design and development in the product cycle. The process transforms some input to an output that has one or more observable response variables. Some of the process variables X1, X2…, Xp are independent, whereas other variables Z1, Z2…, Zp are dependent. The main objective of the experiment is to determine which variables are most influential on the response, even if you can set the influential factors that are near the desired nominal value with small variability and reduce the effects of uncontrollable factors.

3. Results & Discussion

3.1 OpenRocket Simulation Model

Below in figure 3 is the recreated model of the liquid propellant rocket in the OpenRocket Simulator. The top diagram is an internal view of the model, and the lower diagram is an external view of the model. Labeled in the internal view of the model are the GPS, both the drogue and main parachute, the altimeter bay, and the helium and liquid propellant tanks, which contain liquid oxygen (LOX) and liquid methane (CH4). The grey shaded region in the internal view at the lower end of the rocket represents the location of the rocket engine used in the model.

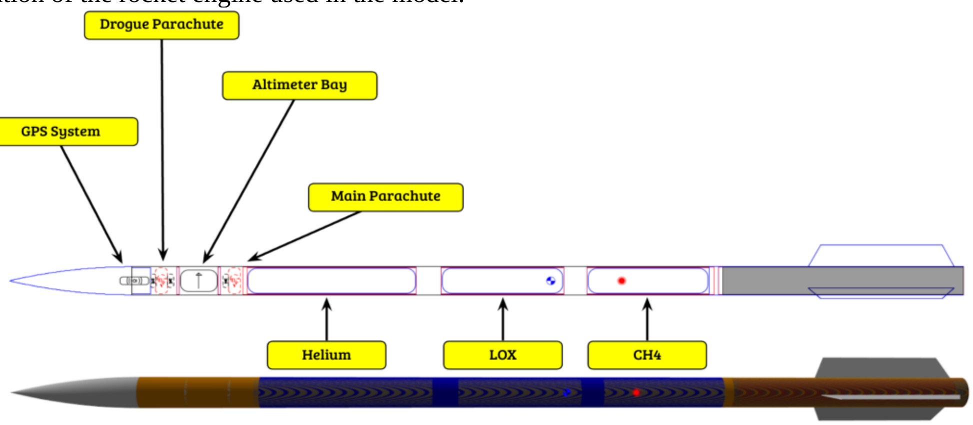

Figure 3. OpenRocket Model of the Liquid Propellant Rocket

3.2 Data Collected (Apogee & Stability)

The data collected from the open rocket simulation experiment was further summarized in figures 4 and 5. Since the response was apogee and stability, the highest average apogee reached, and the average lowest stability values were obtained.

APOGEE (ft)					
		Clipped Delta		Trapezoidal	
		27.5	37.5	27.5	37.5
Fiberglass	21.5	17, 286	17,439	17,100	17,234
	31.5	15,705	15,555	16,867	17,028
	41.5	13,270	6,535	12,355	16,533
Aluminum	21.5	17,152	17,284	17,252	17,435
	31.5	16,580	16,697	16,673	16,840
	41.5	9,827	10,640	13,412	16,286
Carbon Fiber	21.5	17,295	17,426	16,842	17,077
	31.5	16,799	16,919	16,283	16,494
	41.5	9,552	10,420	15,923	15,964

Figure 4. Simulation Results for Highest Rocket's Apogee Reached

STABILITY (cal)					
		Clipped Delta		Trapezoidal	
		27.5	37.5	27.5	37.5
Fiberglass	21.5	5.58	5.64	5.59	5.68
	31.5	4.59	4.66	4.56	4.63
	41.5	3.58	3.66	3.56	3.62
Aluminum	21.5	5.43	5.5	5.41	5.46
	31.5	4.38	4.46	4.37	4.44
	41.5	3.33	3.41	3.32	3.4
Carbon Fiber	21.5	5.58	5.64	5.79	5.83
	31.5	4.61	4.68	4.58	4.64
	41.5	3.6	3.68	3.58	3.64

Figure 5. Simulation Results for Most Suitable Rocket's Stability

These values were recorded by recreating the LPR in OpenRocket, altering the parameters of the tail fin while holding the rest of the LPR's parameters constant, and then running a simulation through the OpenRocket software. For example, to obtain the apogee for a clipped delta fin made of fiberglass at angles of 27.5 and 37.5, the planform shape, root chord, and material were held constant while the angle was changed. After the apogee and stability for both angles had been recorded, the root chord length was then changed to the second of the three lengths and then held constant for both sweep angles, along with the shape and the material. The material was held constant until the sweep angle was altered for both root chord lengths, then the shape was changed once all of the materials were held constant for all of the root chord lengths and the sweep angles.

3.3 Design of Experiments (ANOVA Results)

From figure 5, the summarized data shows that for clipped data, the most suitable stability was (at 3.33cal) with three fins and aluminum as the material. For the trapezoidal fins, the most suitable stability was 3.3, with three fins and aluminum as the material. Overall, from the data, three trapezoidal-shaped fins made of aluminum material give the best stability. Furthermore, from the data, the conclusion that three fins achieve improved stability, and higher material densities for the tail fins, yields a more stable rocket. Additionally, the data concludes that trapezoidal fins achieve better stability than the clipped delta fins. As regards to apogee reached, further analysis performed using Minitab took place. The aim was to investigate which factors (shape, size, material, and quantity of fins) affect the apogee.

Analysis of Variance for Apogee

Source	DF	SS	MS	F	P
Materials	2	96501	48251	1.02	0.409
Quantity	1	1142067	1142067	24.12	0.002
Type of Fin	1	72075	72075	1.52	0.257
Error	7	331500	47357		
Total	11	1642143			

Figure 6. Analysis of Variance (ANOVA)

For this table, source represents the source of the data variation, DF represents the degrees of freedom, SS stands for the sum of squares, MS stands for the mean sum of squares, F stands for the F-statistic of the source, and P represents the p-value of the source. The ANOVA was performed at a 95% confidence interval and the result shows that only the material of fin and planform shape have p values of .409 and .257 respectively. Therefore, it can be concluded that the planform shape has a more significant effect on the apogee reached than the fin material.

3.4 Engineering Drawings (3D Models)

Figure 7 is the 3D drawings of the optimal tail fin designs for apogee and stability made utilizing SolidWorks. The ideal apogee tail fin design is made of fiberglass and has a clipped delta shape. The design parameters are a root chord length of 21.5 in, a sweep angle of 37.5 degrees, a height of 6.5 in, a tip chord length of 16.512 in, and a rounded airfoil cross-section. The ideal stability tail fin design, as shown in figure 8, is made of aluminum and has a trapezoidal shape. The design parameters are a root chord length of 41.5in, a sweep angle of 27.5 degrees, a height of 6.5 in, a tip chord length of 34.732 in, and a rounded airfoil cross-section.

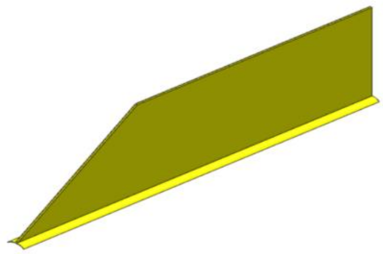

Figure 7. Apogee Tail Fin

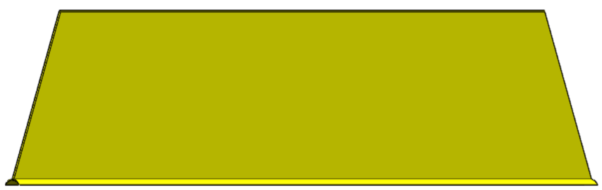

Figure 8. Stability Tail Fin

3.5 Stress & Strain Analysis

Figures 9 and 10 display the amount of stress the different regions of the tail fin experience. The purple arrows represent the location and direction of the force acting on the tail fin. The simulation exposed the tail fins to the amount of drag force they[fins] would endure during flight. Using equation (2) and having obtained the maximum Mach number reached during flights with the apogee and stability tail fins being 1.11 (roughly 829 mph) and 0.98 (729 mph), respectively, the calculated surface area of the leading edge for the apogee fin and the stability fin being $9.84 \times 10^{-3} ft^2$ and $8.82 \times 10^{-3} ft^2$ respectively, the wave drag force was calculated. The max stress the apogee and stability tail fin designs experienced was 106.7 and 632.1 psi, respectively. Given the yield strength of the fiberglass and aluminum material, the apogee and stability tail fins had factors of safety, the yield strength of the material divided by the maximum stress experienced, of 5.91 and 7.31, respectively.

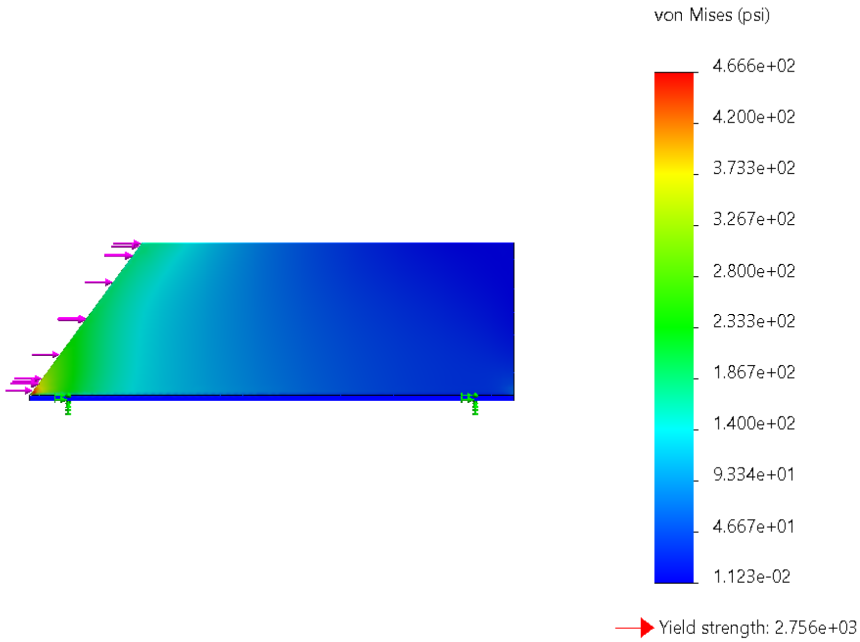

Figure 9. Stress Analysis of Apogee Tail Fin on LPR

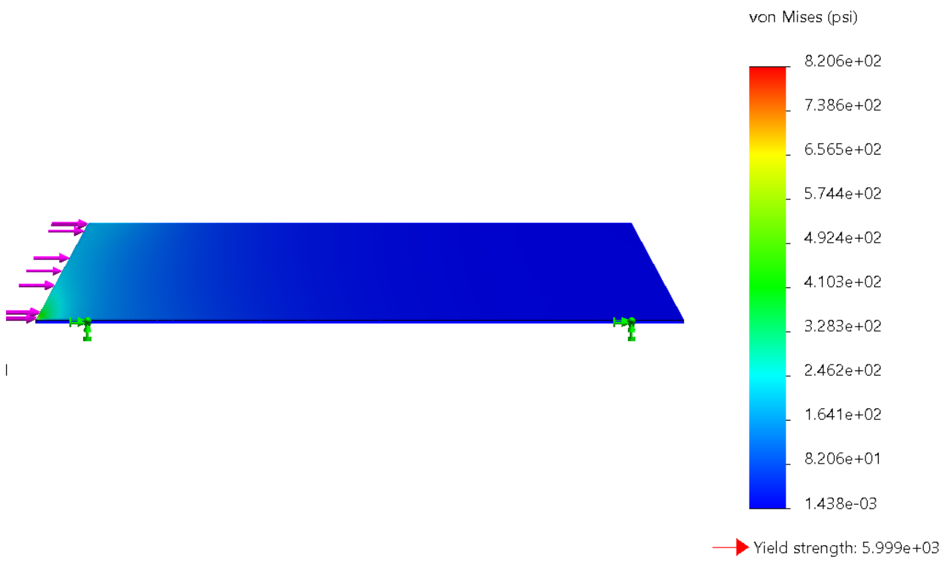

Figure 10. Stress Analysis of Stability Tail Fin on LPR

Another aspect of the tail fin that must be considered when determining if a tail fin is strong enough to withstand the forces during flight is the fin flutter, which is the velocity at which the torque acting on the fin exceeds the fin's yield strength and results in the fracture of the fin. This phenomenon can be simply calculated using equation (3)

$$v_f = a\sqrt{\frac{G}{\frac{1.337(AR)^3 p_\infty(\lambda+1)}{2(AR+2)(\frac{t}{c_r})^3}}} \tag{3}$$

$$p_\infty = 14.694 * \left(\frac{T+459.7}{518.6}\right)^{5.256} \tag{4}$$

Where a is the speed of sound, G is the shear modulus of the material, AR is the aspect ratio of the tail fin, t is the thickness of the fin, c_r is the root chord length, p_∞ is the free-stream static pressure which is calculated using equation (4), and λ is the tip chord to root chord ratio. Assuming the static pressure on an average 70 °F day is 16.425 psi, and the speed of sound is 767.27 mph, plugging in the remaining values of the two tail fin designs, we determine the fin flutter speed for the apogee tail fin is 1809.33 mph, and 1068.07 mph for the stability tail fin. Both of which are significantly greater than the top speed reached by both fins, which were 829 and 727 mph for the apogee and stability tail fins, respectively.

4. Conclusion

This research investigated how the material, geometrical dimensions, and the planform shape affect the apogee and stability of the rocket using the OpenRocket Simulator. The information gathered from the simulations was then used to generate a design for the rocket tail fin that yields the highest apogee and lowest stability. The data from the ANOVA table confirms that of the planform shape and material, the planform shape has a greater effect on the apogee a rocket will reach during its flight than the material. Secondly, using the results gathered from the simulations in figures 5 and 6, it can be inferred that the length of the root chord has a greater effect on the apogee and the stability than the sweep angle. Additionally, two different tail fin designs were made using the highest data values recorded from the simulations for both apogee and stability. The ideal design parameters for apogee were clipped delta-shaped fins made of fiberglass with a root chord of 21.5 in and a sweep angle of 37.5 degrees. The ideal design parameters for stability were trapezoidal-shaped fins made of aluminum with a root chord of 41.5 in, and a sweep angle of 27.5 degrees.

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