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Fin Optimization for Enhanced Flight Performance of an Experimental Rocket

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Abstract

Rocket fins provide the necessary aerodynamic applications required for a rocket to reach an ideal flight performance. An experimental rocket was designed and manufactured for participation in the October Skies launch event. The rocket flew at a maximum altitude of 4260ft with a maximum speed of Mach 1.38. The flight data and the simulations performed in FASTRAN and OpenRocket showed that the drag coefficient for the turbulent conditions yielded an error of 1.45%. It was found that under ideal laminar and zero wind conditions, a drag coefficient of 0.484 would have been acting on the rocket, meaning that the drag coefficient increased by a factor of 13.6%. For this experiment, new fins are currently being designed so the rocket can achieve a maximum speed and altitude while minimizing the coefficient of drag. The fins will be optimized to meet the current design limitations of the rocket fuselage. From trials and experimentation using OpenRocket software and calculations, two designs have met the mission requirements and in addition, one of these fin designs was used on an experimental flight test as part of our investigation to see the impact of the flight performance. This paper will show the optimization methodology, flight tests and results of our investigation.

Keywords: Optimization, Flight Performance, Fins

1. Introduction

The field of experimental rocketry involves experimenting with different scale rocket designs. Many flight engineers tend to optimize kit-based internal designs developed in the early 2000s to achieve upgraded performance. The problem with optimizing the internal design of the rocket is that the change in weight can severely affect the stability of the rocket, which can then lead to a massive flight path deviation or even a crash. High grade motors come in different sizes; however, the cost of each motor increases as the power level increases. Rockets can be stable using both active and passive control methods. At the university level, rockets that are not FAA certified class 1 with active control systems can be mistaken for guided weaponry[7]; therefore, fins are installed on the rocket as a passive control system. Most experimental rockets are equipped with different fin designs based on the height and weight of the main rocket fuselage. Rocket fins provide longitudinal stability and aerodynamic efficiency. A rocket will undergo inertial forces during its flight phase which could sometimes change its flight path, thus affecting its peak altitude performance. Rockets also wobble inflight due to the inertial forces and requires excess propellant to help stabilize itself, which in turn affects speed performance. Fins can have four different cross sections: rectangular, airfoil, rounded and wedge. Each of these cross sections have their own unique properties that can either make or break a rocket's flight performance based on the mission specifications. Optimal flight performance can be achieved when the drag is minimum and rocket is mostly stable throughout its flight. While other factors such as weight, drag and other aerodynamic factors were considered in this experiment, the purpose was to investigate the effect of changing the fin design on the rocket's flight performance.

2. Design and Methodology

Based on the mission guidelines with safety protocols enforced by the NFPA1127[7], Two Aerobee 150A rockets were developed with one rocket equipped with the initial trapezoidal fin design and the other rocket equipped with the newly optimized fin design. An initial preflight conducted on the initial trapezoidal configuration showed that the rocket was unstable due to the improper positioning of the Center of Gravity (CG). Upon adding weight into the nose, it was found that the rocket was within the stability criteria, however, from the flight tests it was found that the altitude and speed performance deteriorated by 4% bringing the top speed down to Mach 1.38 due to extra weight in the rocket. Therefore, our analysis began by modelling fins which would maintain the stability of the rocket. The Barrowman equations provide optimal parameters to assist in optimization of the fins; however, the disadvantage of using this method is that accurate designs cannot be achieved due to certain limitations involving the static margin. For a rocket to be stable, the static margin needs to be on or near the empennage of the rocket. This means that the Center of Pressure (CP) must be near or between the center of the of the leading edges of the fins and the center of gravity must be in front of it at a distance twice the diameter of the rocket[3].

The shape of a fin greatly affects the flight performance of the rocket. The worst shaped fin would have the highest induced drag; that is, more air flowing around the tip edge of the fin. Therefore, avoiding fins with a larger area near the fin tip was taken into consideration. Lifting forces are not required when the rocket is flying straight upward; however, as the rocket tends to deviate from its path due to the air turbulence and wind, the inflight lift generated by the angle of attack of the rocket due to those perturbations tends to stabilize the rocket. Theoretically, elliptical fins are ideal as they provide the best lifting force; however, they also produce enough induced drag to also provide drag stability to the rocket[1]. Clipped Delta fins are primarily used on high performance rockets to yield a low drag force[2]. The elliptical and clipped delta configurations provided more positive figures of merit compared to the other types of fins[1]. A combination of the two fins was considered and the resulting Samurai Sounder configuration (Figure 2) was developed. Figures 1 and 2 show the OpenRocket modelling of the initial and the optimized configuration of the fins with its CG and CP positions. The position of the CP and CG are both shifted back in the optimized configuration, allowing the rocket to be marginally stable and well within the limits of a safe flight.

One of the difficult decision factors of pinpointing an accurate design was figuring out the appropriate cross section and sweep for the fins. Most fins used in high powered experimental rocketry employ rectangular, rounded, airfoil or wedge based cross sections[6]. Most of these cross sections were studied based on theoretical data, past flights and simulations and was determined that for the nature of this mission, a combination had to be made. Rectangular fins in the past flights, though high-performing, create high drag forces which negatively impact the flight performance at higher speeds[4]. Therefore, to test the effective performance impact of the fins the rockets were initially equipped with rectangular-airfoil hybrid cross section fins with tapered ends. Figures 3 and 4 show the final 3-D design of the rocket.

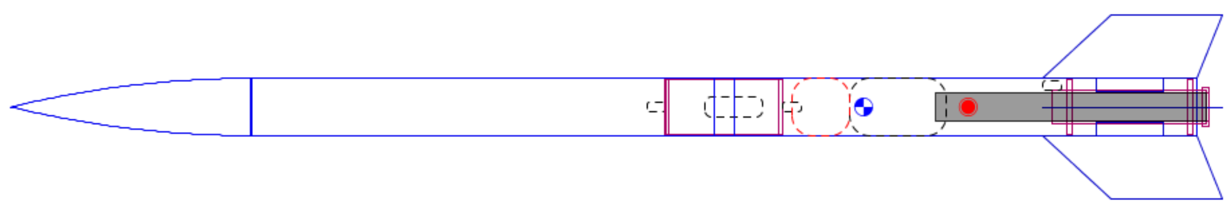

Figure 1. Industrial Trapezoidal Fin Configuration

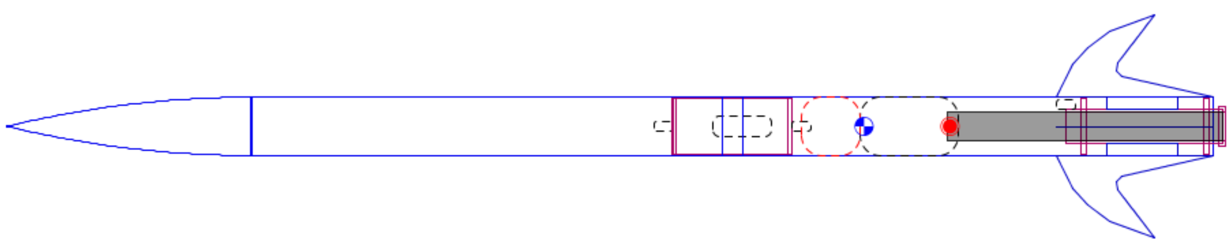

Figure 2. Samurai Combination

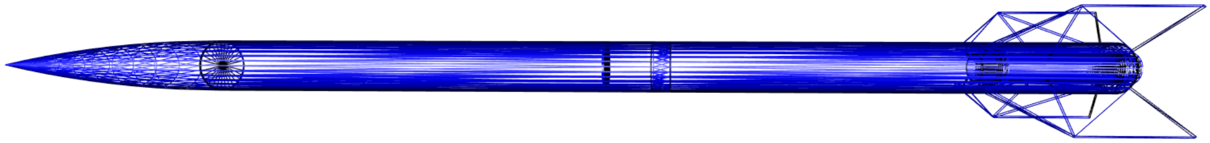

Figure 3. Industrial Trapezoidal Fin Configuration

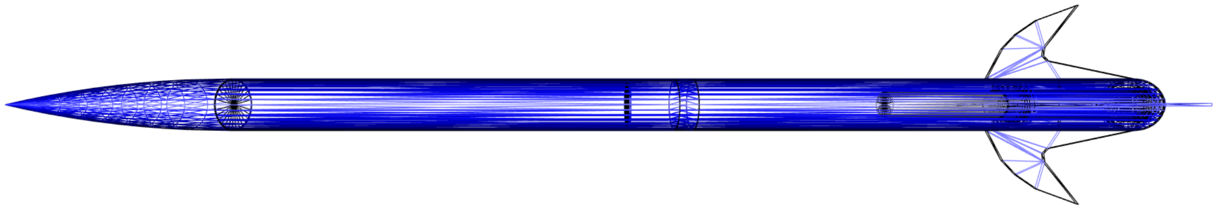

Figure 4. Samurai Combination

The new fins have a lower area compared to the initial design. To reduce the effects of the shockwaves at supersonic speeds, the span and the sweep angle was further increased. Initially, the software indicated that the rocket equipped with the new fins would be marginally stable. However, upon investigating the different cross-sections, input in the software for this configuration, the airfoil cross-section showed that the static margin would be between 1.0 to 2.0, therefore, rocket would be well within the stability criteria.

OpenRocket simulations showed that the rocket's CP was near the tail end of the rocket, which significantly increased the margin of error for the static margin of the rocket. However, Rocksim demonstrated that the CP was a bit closer to the CG. Therefore, we decided to take the average of the two distances to be the actual CP which still showed that the rocket could perform a stable flight. Theoretical simulations performed in OpenRocket for altitude performance showed that the new configuration would reach an average peak altitude above 4200 ft.. A sounder rocket has the capability to fly at a speed more than Mach 1.2. However, as the speed of the rocket increases, the drag force also increases, impacting the altitude performance of the rocket. A more in-depth simulation was performed using the RockSim software to investigate how much drag was being produced (See Figures 4 and 5), its peak altitude, and understand the rocket's behavior in flight (See Figures 6 and 7).

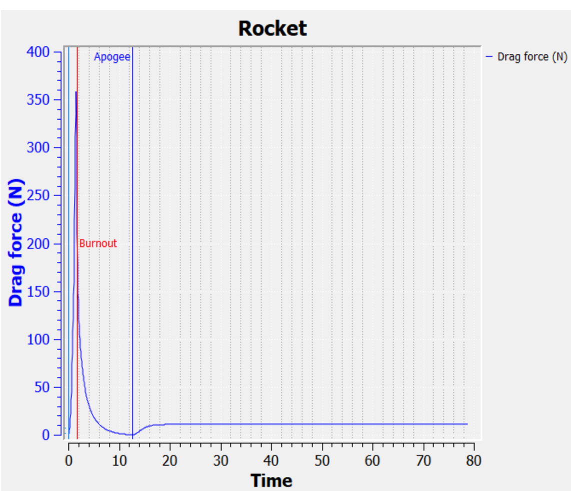

Figure 4. Drag Force of the Optimized Rocket

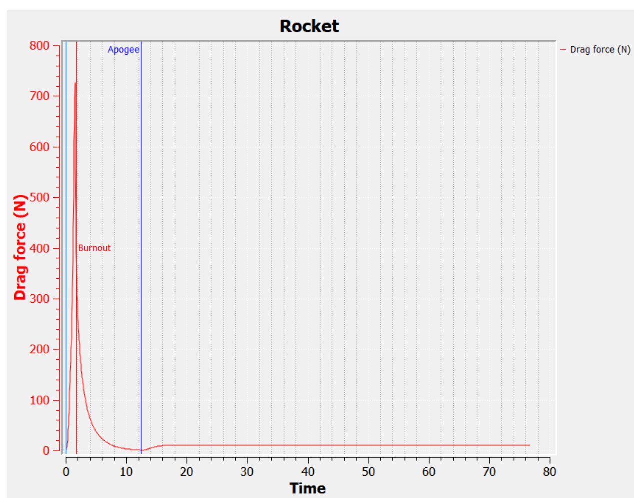

Figure 5. Drag Force of the Original Rocket

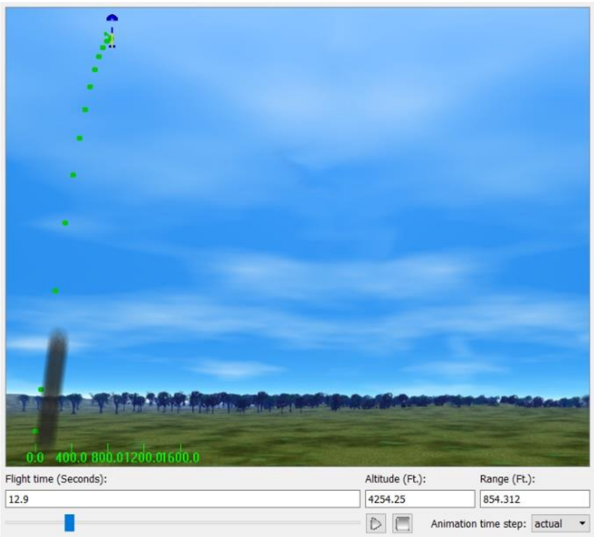

Figure 6. Flight profile of the optimized design.

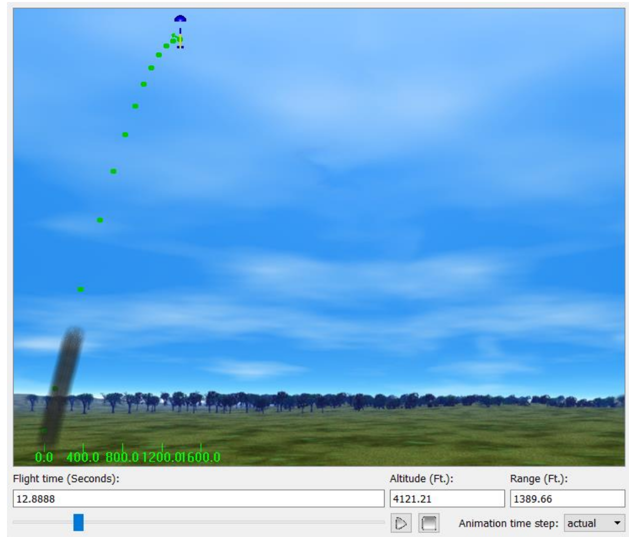

Figure 7. Flight profile of the original rocket.

Table 1 summarizes the simulation results for the altitude, speed and drag force for each configuration from the graphs generated in figures 4 and 5.

Table 1. Simulation Results

Configuration	**Altitude**	**Speed**	**Drag Force**
Initial Trapezoidal Configuration	4,121ft	1,500 ft/sec	700N
Samurai Combination (optimized configuration)	4,265ft	1,850 ft/sec	350N

The results of the simulations performed (in figures 4 and 5) showed that the initial trapezoidal configuration exerts a drag force of about 700N. The newly optimized fins exerted a force half of the initial configuration which in turn improved its altitude performance. The new design of the fins, while keeping the same thickness provided a reduction in the overall weight of the rocket. This in turn positively affected the overall flight time of the rocket by 8 seconds.

A final specification for the Samurai Sounder's optimized design is shown in table 2 and figures 3 and 4 show the comparison with the original design.

Table 2: Rocket's final dimensions

Overall Fuselage Length	62.125
C.P. (from the nose tip)	50 inches
C.G. (from the nose tip)	45 inches
Motor Type	Aerotech J-425
Mass of the rocket	51.6885
Inner tube diameter	3 inches

The rockets were launched at in similar weather conditions to investigate the impact of the optimized fin design on its overall flight performance.

3. Flight Test

Targeted ideal flight conditions of a high powered rocket for this mission was warmer temperatures with light and variable winds. Since the experiment took place during the winter season, the launches had to be delayed in order to meet the temperature and pressure requirements. Table 3 shows the translated METAR data of the launch area (Fresno, CA, meteorological identifier KFAT) at the time of launch.

Table 3: Flight Parameters at the time of launch

Temperature	64.9 F
Pressure	30.16 in
Launch Time	11:45 A.M
Winds	5.8 mph
Humidity	27%

Preflight checks determined the departure weight of the modified rocket to be 13 lbs and 13.25 oz, lighter than the original rocket (15 lbs.) Installation of the motor before the launch sequence yielded a CG imbalance for the original design. This was rectified by placing additional weight into the nose cone of the rocket to bring the CG forward. This increased the weight of the rocket, which ultimately increased the drag forces and thus hampered its overall speed performance.. As the CP shifted towards the tail end of the rocket for the second design, the position of the CG after the motor installation provided a good static margin. The visual representation of the flight showed that the rocket was very stable. Figure 8 demonstrates the flight data from the initial configuration and Figure 9 from the optimized configuration.

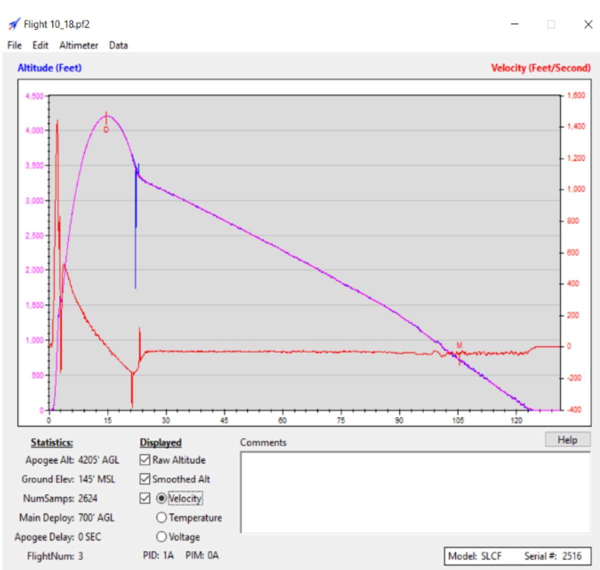

Figure 8 – Flight Data from Original Rocket

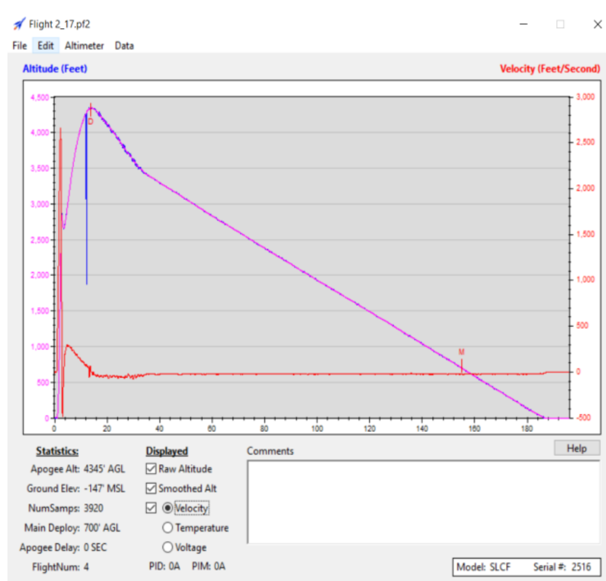

Figure 9 – Flight Data from the Optimized Rocket

4. Discussion

The availability of OpenRocket and Rocksim software provided an ideal viewpoint of the rockets behavior during its flight phase by optimizing the design in the software itself, showing both results in Barrowman method and Rocksim Method. The rocket was stable and had an uneventful flight, and was later certified as a successful test flight by Tripoli Area Prefecture (TAP) officials. The resulting simulations on Rocksim showed that the newly optimized rocket experienced a 50% reduction in the overall drag force, thus reducing the drag coefficient and the flight time. The peak altitude increased by a factor of 1.2%. Attaining the proper static margin without affecting the rocket's weight contributed to the decrease in drag forces acting on the rocket. The simulations revealed a 10% error in the static margin readings. The sounding rocket's main body design dictated that the static margin of the rocket had to be more than twice the diameter of the rocket. The static margin determined at the time of the preflight was exactly twice the diameter. The first configuration, however, took on an additional 2lb 12oz to meet the appropriate static margin requirement. Inflight experimental data showed that the first configuration reached a peak altitude of 4205ft with a max velocity of Mach 1.386. The optimized configuration reached a peak altitude of 4347ft with a maximum velocity of Mach 2.39. The speed performance for the newly optimized rocket increased by a Mach number. However, that limited the altitude performance of the rocket due to excessive drag at supersonic speeds. However, the rocket still climbed to a peak altitude that was 142ft greater than the simulated altitude. The first rocket, due to the additional 2lbs weight, experienced more drag than predicted from the simulations, which negatively impacted the altitude and speed performance.

5. Conclusion and Future Work

The flight test conducted showed that the proposed optimized fin design, which has a lower fin area but a larger fin span, successfully improved the rocket's altitude and speed performance. The rocket's overall weight decrease showed that optimizing the fins can impact the overall rocket's physical and flight parameters. Currently, ANSYS Fluent is being used to conduct flow analysis of the newly optimized design. An enhanced version of the fins is currently being designed. The newer designs will be manufactured using both fiberglass and carbon fiber and further flight tests are scheduled to be conducted.

6. Acknowledgements

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