How Do Various Fin Profiles Affect Aerodynamics in Model Rockets?

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Abstract

Model rocket fins are essential components during a model rocket's flight. Without them, flight stability and apogee are both compromised. However, there are many fin shapes, profiles, and structures that one can incorporate into their model rocket design, with each distinct fin set design affecting the rocket's aerodynamics. There are many different opinions on what fin shape performs the best and what fin shape performs the worst, along with why certain fin shapes behave in their respective ways. We decided to put these ideas to the test; to discover what effects each fin profile has on its parent rocket, we ran multiple experiments in the form of launching several rockets, each with a different set of fins. In this research paper, twelve different fin shapes and profiles are tested, analyzed, and compared for their various flight performances. Following the experiment, the effects of fin shapes on a model rocket are studied and analyzed in more detail, and the reasons for these changes are thoroughly investigated. The fin shapes we tested include trapezoidal symmetrical, trapezoidal delta, trapezoidal swept, and elliptical. The fin cross-sections we tested include square, rounded, and airfoil. Through this paper, we seek to learn more about not just why each fin set affects a rocket in a certain way, but also about aerodynamics and the behavior of airflow in general.

Introduction

During a rocket launch, one of the most important aspects of its flight is the rocket's stability. A rocket is stable if it can counter the dynamic forces it is subject to, exerted by the rocket motor's thrust, weight, and atmospheric effects, including drag and wind. An unstable rocket would be extremely chaotic, unpredictable, and hazardous.

According to Van Milligan (2018), in an Apogee Rockets newsletter, a rocket's stability is determined by the location of the rocket's center of gravity (CG) and the location of the rocket's center of pressure (CP). "The definition of Center-of-Pressure is the point on the rocket where all the aerodynamic forces balance," Van Milligan (2018) says (p. 2). Van Milligan also says that you can use a 2-dimensional cutout of a rocket to find the CP – this can be found at the point at which there is an equal amount of *surface area* both forward and aft. The rocket's CG is defined as the point at which there is an equal amount of *mass* both forward and aft; thus, you can determine a rocket's CG by finding the point at which you can balance the rocket on your finger or the edge of a ruler (Van Milligan, 2018).

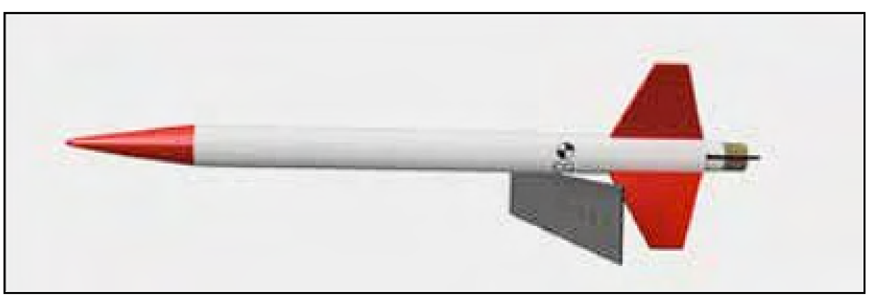

Fig. 1: A visualization of balancing a model rocket on the edge of a ruler, revealing its CG. ([Photograph of balancing a rocket on the edge of a ruler], Van Milligan, 2018) [1]

Van Milligan also says that a rocket is more stable the further back the CP is from the CG; however, a rocket is less stable if the CP is too close to the CG, and a rocket is completely unstable and unpredictable if the CP is ahead of the CG. This is because airflow that is not parallel to the rocket's trajectory will result in torque that rotates the rocket about its CG; however, since the CP is further aft than the CG, once the rotation aligns the rocket to the airflow, the torque is effectively eliminated and the rocket stays parallel to the airflow. A diagram to illustrate this idea is seen below:

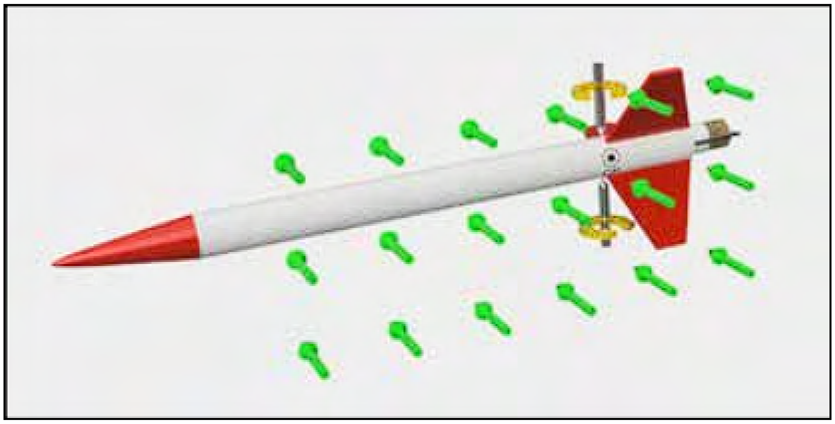

Fig. 2: A diagram illustrating how an aft CP helps eliminate angular momentum derived from gusts of wind. ([Diagram of how CP keeps a rocket parallel to the wind], Van Milligan, 2018) [1]

Thus, when one designs and constructs a rocket, it is essential to make sure our CP is at least one body tube diameter behind the CG (this is a common rule of thumb in model rocketry) (Van Milligan, 2018).

Since the rocket's CP is directly dependent on the rocket's surface area distribution, it would make sense to think that one could make the rocket more stable by adding surface area to the back of the rocket. This is the exact principle behind rocket fins – adding surface area to the back of the rocket to pull the CP back and, in turn, increase rocket stability.

There are many shapes, sizes, and materials from which you can make rocket fins. One property of fins, particularly trapezoidal fins, is called the sweep angle. Wood (2022) defines sweep angle as "...the angle at which the wing is translated backwards (or occasionally forwards) relative to the root chord of the wing." (para. 2) [1] [2]

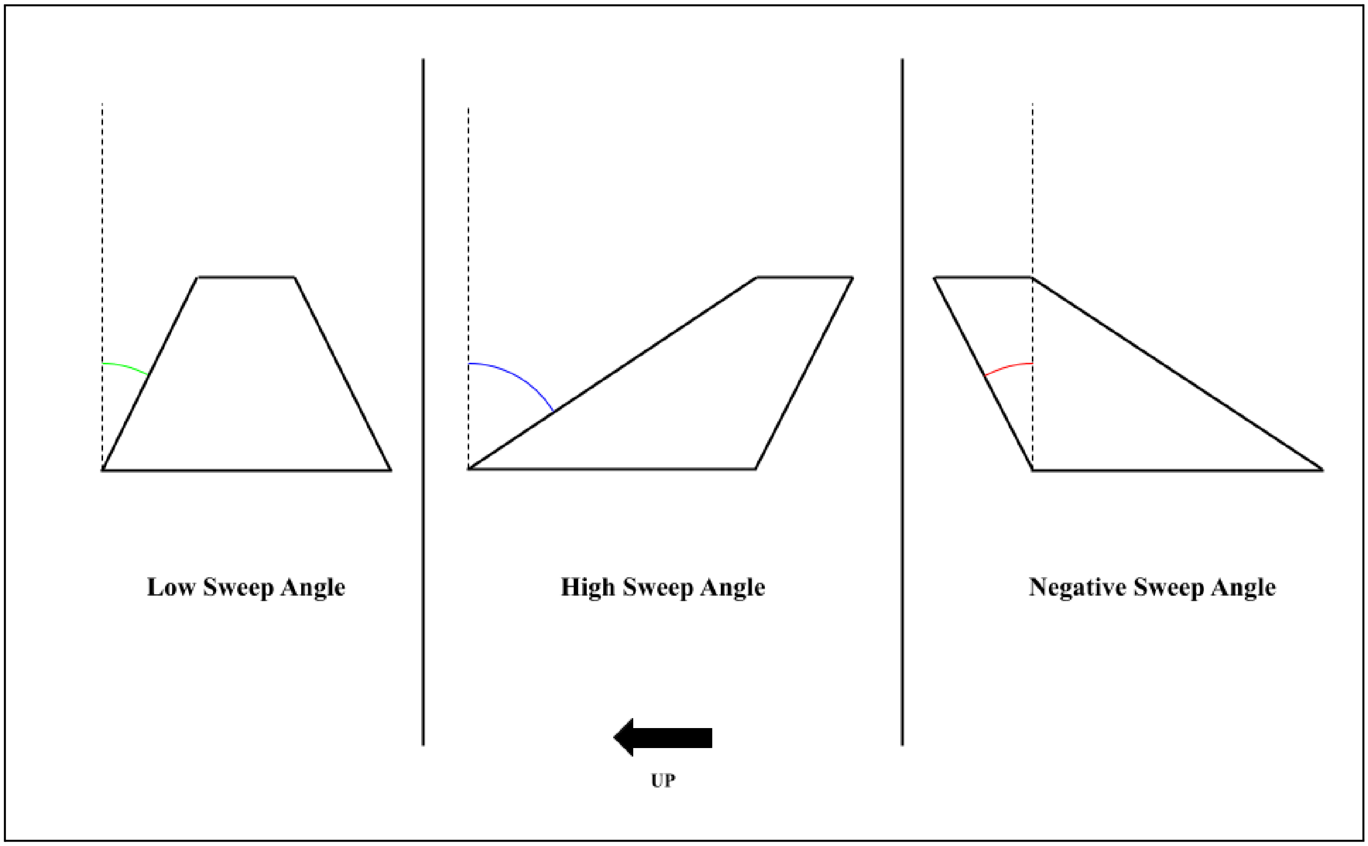

Fig. 3: Three fin designs with varying sweep angles. The low sweep angle design could be called "symmetrical", since it is symmetrical along the vertical axis, and the high sweep angle design could be called "swept".

As we can see in Figure 1, some fins have a high sweep angle, some have low sweep angles, and some even have negative sweep angles – meaning that their tip chord is forward instead of aft. Since fins do not just affect CP, but also have mass, the shapes and sizes of rocket fins will heavily influence the behavior of the rocket.

But how exactly does fin shape and structure influence the trajectory and apogee of a rocket? How exactly does a more swept-back fin affect the rocket's drag? How does the cross-section of a fin (square, rounded, airfoil) impact the rocket's apogee? These are the questions this research project aims to answer – and to answer them, we conducted multiple experiments to further research and analyze fin aerodynamics.

Our Hypothesis and Other Relevant Work

This experiment has 2 criteria: fin shape and fin cross-section. There are 4 distinct fin shapes: trapezoidal symmetrical, trapezoidal delta, swept trapezoidal, and elliptical.

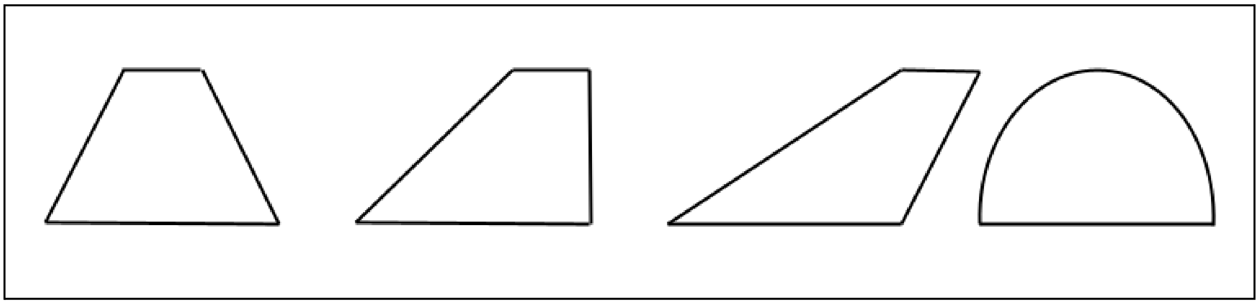

Fig. 4: A visualization of each of the four fin shapes. From left to right: trapezoidal symmetrical, trapezoidal delta, trapezoidal swept, and elliptical.

	Trapezoidal Symm:	Trapezoidal Delta:	Trapezoidal Swept:	Elliptical:
Root Chord (in)	3	3	3	3
Tip Chord (in)	1	1	1	N/A
Sweep Angle (°)	26.6	45	56.3	N/A
Height (in)	2	2	2	2
Maximum Thickness (in)	0.125"	0.125"	0.125"	0.125"
PLA Infill (%)	50	50	50	50

Fig. 5: The specifications of each of the four fin shapes. All fins' root chord, height, maximum thickness, and PLA infill are the same.

Additionally, there are 3 distinct fin profiles: square, rounded, and airfoiled.

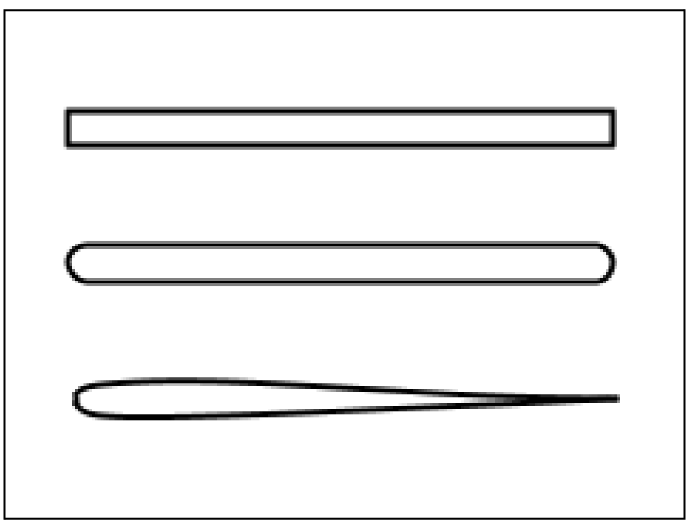

Fig. 6: A bird's-eye-view visualization of each of the three fin cross-sections. From top to bottom: square cross-section, rounded cross-section, and airfoil cross-section.

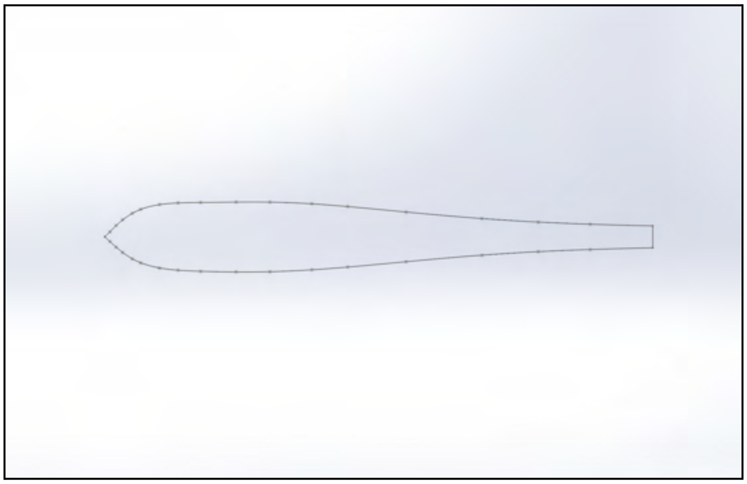

Fig. 7: A bird's-eye-view visualization of the splines used in SOLIDWORKS for Makers to make the airfoil cross-section fins.

All of our fins were 3D-printed and were composed of PLA material. PLA, also known as polyactic acid, is a common 3D-printing filament and is the easiest fin material to use for our project. During the printing of our fins, we considered switching to PETG, a more heatproof solution better suited for the high temperatures experienced in model rocketry. However, PLA ended up being the best choice due to its ease to use. We are 3D-printing our fins to save the cost of purchasing countless sets of fins. It should be noted that 3D-printed fins, especially when being used on mid or high-power rockets, are heavily advised against due to their fragility in comparison to stronger materials such as plywood or fiberglass. We are only allowing 3D-printed fins to be used for this research project since our rockets are classified as low-power.

Now that our research scope is fully established, we can proceed with analyzing the findings of others.

There are 2 main claims regarding the impact of fin shape on flight trajectory and apogee. The first claim is backed up by Tim Van Milligan, et al [ref. 5] and a few other sources published as science fair papers by Batscha (2012) and Dhyaram (2018) from the California Science & Engineering Fair. This claim states that trapezoidal symmetrical fins result in the highest drag and the lowest apogee, while elliptical fins result in the lowest drag and the highest apogee (Van Milligan, 2017; Batscha, 2012; Dhyaram, 2018) [3] [4] [5]. This first main claim appears to be the most popular among most rocket flyers and hobbyists.

The second main claim is similar, stating that trapezoidal symmetrical fins result in the lowest apogee, while trapezoidal fins with a high sweep angle result in the highest apogee. Notice the difference – while the first claim states that elliptical fins reach the highest altitudes, the second claim states that swept-back trapezoidal fins reach the highest altitudes. Unlike the first claim, this second main claim is mainly supported by computer simulations such as OpenRocket and RockSim.

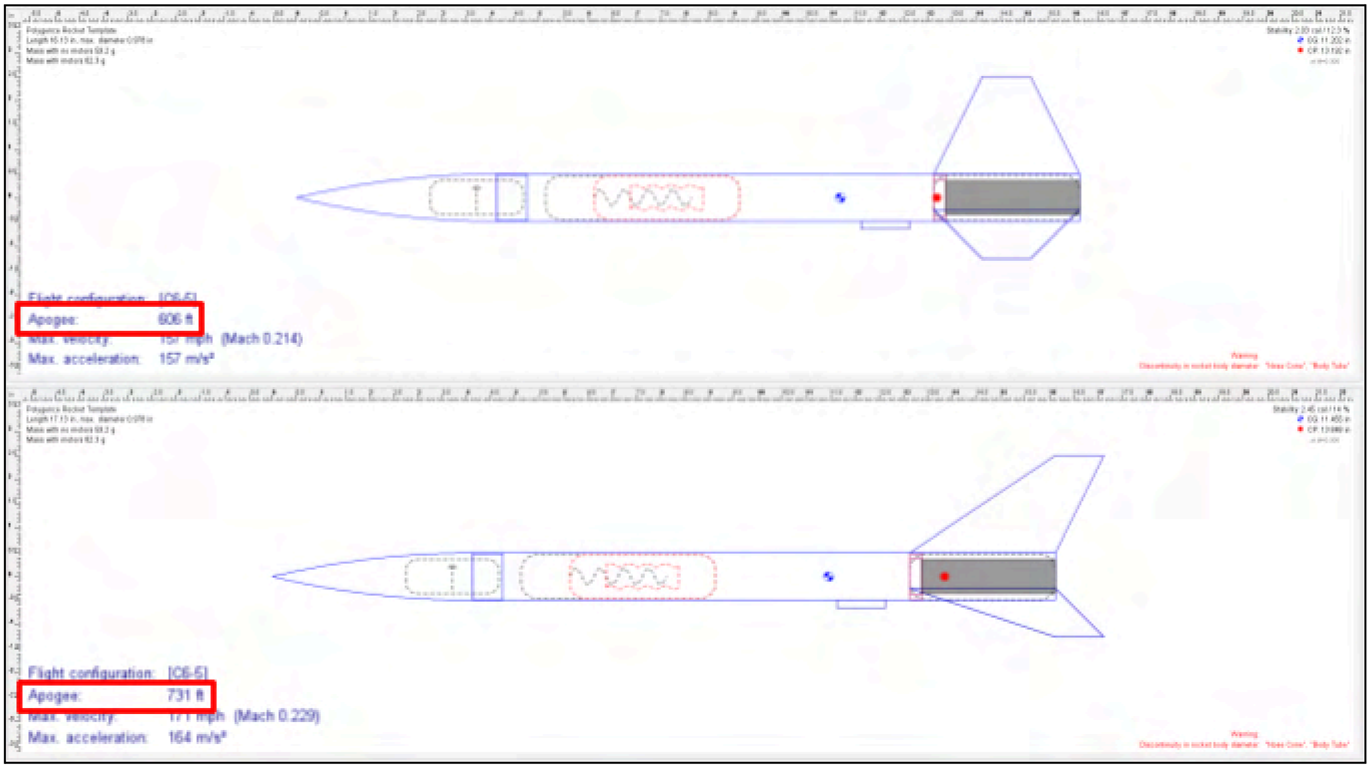

Fig. 7: A visualization of the second claim; during testing in OpenRocket 24.12, trapezoidal swept fins perform the best at 731 feet, and trapezoidal symmetrical fins perform the worst at 606 feet.

To conclude, here are two quick descriptions of each main claim:

- Claim 1: Trapezoidal symmetrical fins result in the lowest apogees, while elliptical fins result in the highest apogees
- Claim 2: Trapezoidal symmetrical fins result in the lowest apogees, while trapezoidal swept fins result in the highest apogees

Van Milligan (2017) backs up the first claim by stating that elliptical fins produce the least “induced drag”. As a fin generates lift, the pressure difference between the top and bottom of the fin causes air to spiral at the tip chord, creating vortices. This concept of spiraling air gaining angular momentum as it attempts to equalize the air pressure difference is not unique – the same phenomenon occurs at a much larger scale in tornadoes and is a very familiar and common occurrence in the aviation field. In fact, according to Boldmethod (2022), this is the exact reason that most modern airliners have wingtips; these shapes on the ends of both wings help disrupt airflow and mitigate induced drag. Van Milligan (2017) argues, “The reason the elliptical fin has the lowest induced drag is that the shape of the fin orients more of the lift force closer to the body tube of the rocket because the fin is longer near the body tube. That means there is less of a lift force created near the tip of the fin because the fin is shorter in that section of the fin.” (p. 4) [3] [6]

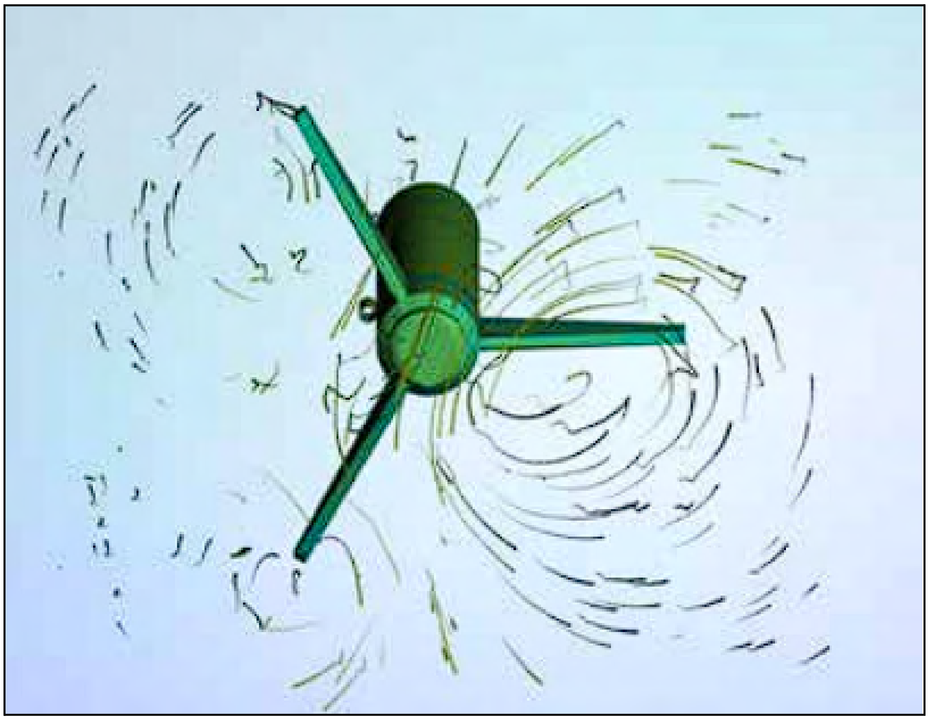

Fig. 8: A computer simulation displaying how vortices are created at model rocket fin tips. ([Photograph of a computer simulation showing air vortices at model rocket fin tips], Van Milligan, 2017) [3]

After analyzing others' relevant work, our fully developed hypothesis is that swept-back, trapezoidal fins result in the highest altitude, and trapezoidal, symmetrical fins result in the lowest altitude. We also think elliptical fins result in the second-lowest altitude, and trapezoidal delta fins result in the second-highest altitude.

Swept-back fins produce the best results because swept-back fins pull the CP back towards the aft more than the other fin shapes, which, as mentioned before, make the rocket more stable. Additionally, the streamlined shape of swept-back fins produces less drag than the other 3 fin shapes. We also believe that elliptical fins produce better results than trapezoidal symmetrical fins despite their somewhat similar proportions and surface area because of their curved edge, which is more aerodynamic than the sharp turns seen in trapezoidal symmetrical fins' geometry.

Among the 3 cross-sections (square, rounded, airfoil), square cross-section fins would reach the lowest altitude, airfoiled fins would reach the highest altitude due to their streamlined design, and rounded fins would be somewhere in the middle, since they are more streamlined than square fins but less ideal than airfoiled fins.

This concludes our hypothesis, allowing us to proceed with laying out the plan for our experiment.

Test Apparatus

This experiment tested 4 fin shapes and 3 fin cross-sections. Our 4 fin shapes include trapezoidal symmetrical, trapezoidal delta, swept trapezoidal, and elliptical. Our 3 fin cross-sections include square, rounded, and airfoil. When we insert these 2 criteria into a matrix, we get 12 different combinations of fin sets.

Building and flying 12 individual rockets for each fin set would be impractical. This is why we created a way to quickly and efficiently swap out and reuse fins, allowing us to only construct 3 primary rockets instead of 12 and one extra rocket as a spare in case one rocket gets lost. What we have created is called a fin rail: it allows fins to be removed and reattached without glue or any other adhesive. It's also easy and practical to create, being made of PLA and 3D-printing in under 2 hours. 3 of them are attached to a model rocket (since there are 3 fins to attach), and the fins slide in and out through the rail, creating an efficient way to avoid the impracticality of constructing several rockets.

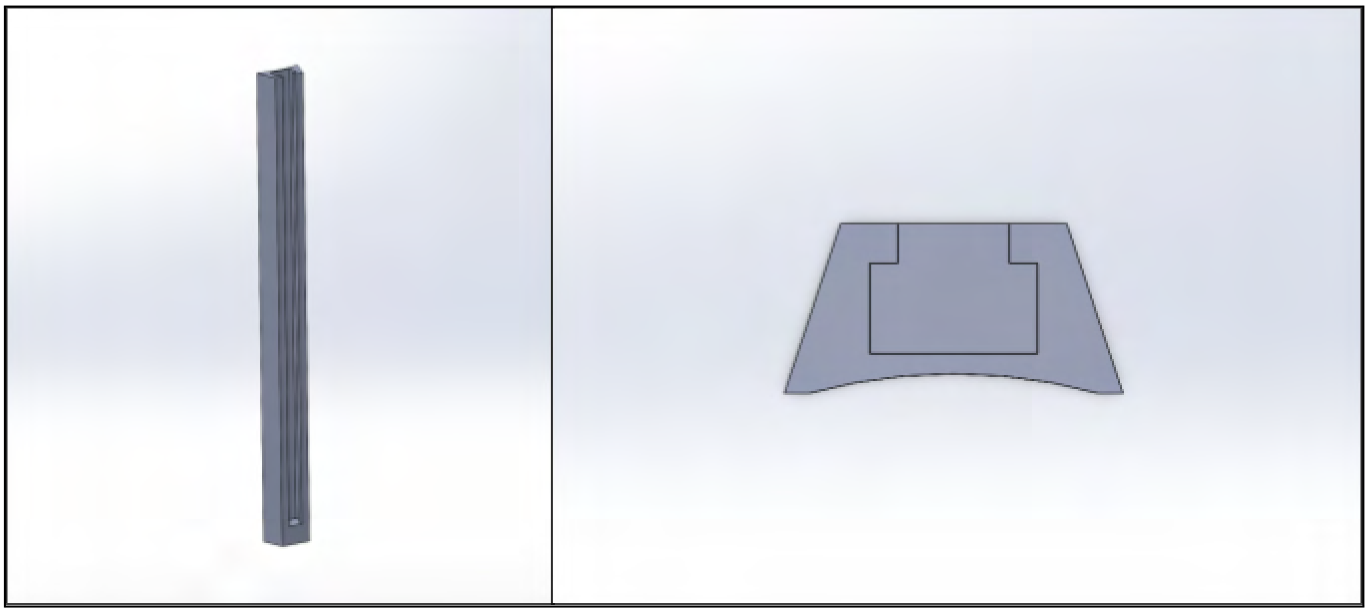

Fig. 9: Two views of our fin rail inside of SOLIDWORKS for Makers. One view is from the side, and another view is from the top down.

All 3 rockets were identical to each other – they were constructed with a 12" BT-50 body tube, a PNC-24C nosecone, and an 18-24mm motor adapter, just to name the major components. All rockets flew on an Estes C6-5 motor, and the data was recorded using a JollyLogic AltimeterTwo kept in the nosecone of each rocket.

Experiment

Each fin set has a unique name, composed of one uppercase letter and one lowercase letter. The uppercase letter defined the fin shape, while the lowercase letter defined the fin cross-section. We created a matrix to display this idea.

	S(ymmetrical)	**D**(elta)	(s)**W**(ept)	**E**(lliptical)
s(quare)	Ss	Ds	Ws	Es
r(ounded)	Sr	Dr	Wr	Er
a(irfoil)	Sa	Da	Wa	Ea

Fig. 10: our matrix for displaying each fin set's unique name. Uppercase letters S, D, W, and E define fin shape, while lowercase letters s, r, and a define fin cross-section.

We have also created a simple spreadsheet to stay organized during the launch day and keep track of which launches have already been executed and which ones are next.

	A	B
1	Ss	Ds
2	Ws	Es
3	Sr	Dr
4	Wr	Er
5	Sa	Da
6	Wa	Ea

Fig. 11: our organizational spreadsheet for the launch day. The A column is for one rocket, and the B column is for the other.

With all the plans set in place and the organizational spreadsheets made, it is time to prepare for the launch and execute the experiment.

Fig. 12 (left): One of our rockets flying into the sky a few seconds after ignition.
Fig. 13 (right): One of our rockets beginning to lift off from the launchpad.

Fig. 14: One of our rockets approximately 20 feet above the ground just as it lifts off.

Fig. 15 (left): One of our rockets' contrails can be seen against the blue sky.
Fig. 16 (right): One of our rockets reaches apogee several seconds after ignition.

Following the experiment, we obtained the following results.

	Trapezoidal Symm.	Trapezoidal Delta	Trapezoidal Swept	Elliptical	AVG
Square	527	553	559	543	545.5
Rounded	545	548	588	529	552.5
Airfoiled	692	687	694	682	688.75
AVG	588	596	613.67	584.67	
	RED = low performance				
	YELLOW = mediocre performance				
	GREEN = best performance				

Fig. 17: The results from the experiment. Conditional formatting was used; cells colored red performed relatively low, while cells colored green performed relatively high. All data is interpreted in imperial feet.

At this point, we were set to analyze our results and discover why certain phenomena may have occurred. This helped us better understand how fins affect a rocket's trajectory.

Analyzing Our Findings

Our hypothesis was correct in predicting which fin sets would yield the highest altitudes – the trapezoidal swept shape obtained the highest apogee in all 3 rows, and the airfoil cross-section obtained the highest apogee for all 4 fin shapes by far. Our reasoning for this is the same as our argument for our hypothesis: the more swept back a set of fins is, the further back the CP is, thus stability is increased, and the more aerodynamic the rocket is. Additionally, an airfoil cross-section flows through moving air much more easily and produces less drag than square cross-sections or rounded cross-sections, which is why airfoil cross-section fin sets obtained the highest altitudes.

Despite these correct predictions, our hypothesis was not entirely accurate. For example, We predicted that trapezoidal symmetrical fins would be the worst-performing fin shape out of the four. However, elliptical fins actually performed worse than trapezoidal symmetrical fins by just a couple of feet, defying our expectations.

	Trapezoidal Symm.
Square	527
Rounded	545
Airfoiled	692
AVG	588

Fig. 18: This table compares the data of the trapezoidal symmetrical fin shape and the elliptical fin shape. Elliptical fins, as seen in the bottom row, perform ever so slightly worse than the trapezoidal symmetrical fins. Conditional formatting was used; cells colored red performed relatively low, while cells colored green performed relatively high. All data is interpreted in imperial feet.

Additionally, we initially believed that trapezoidal delta fins would fall somewhere in between trapezoidal symmetrical and trapezoidal swept fins. And while this is true, trapezoidal delta fins surprisingly perform more similarly to trapezoidal symmetrical fins than trapezoidal swept fins, showing how trapezoidal swept fins are the best-performing fin shape by a wide margin.

	Trapezoidal Symm.	Trapezoidal Delta	Trapezoidal Swept
Square	527	553	559
Rounded	545	548	588
Airfoiled	692	687	694
AVG	588	596	613.67

Fig. 19: This table compares the data of the trapezoidal symmetrical fin shape, the trapezoidal delta fin shape, and the trapezoidal swept fin shape. As seen by the averages at the bottom, trapezoidal swept fins surpass the other two fin shapes in performance by far. Conditional formatting was used; cells colored red performed relatively low, while cells colored green performed relatively high. All data is interpreted in imperial feet.

One aspect of the received data that was surprising was the unusual lack of variation among the airfoil cross-section fin sets. The other cross-sections show large variations between fin shapes, with differences sometimes up to 70 feet between profiles. Additionally, apogees among fin shapes follow a distinct pattern in the square cross-section row and the rounded cross-section row: trapezoidal symmetrical or elliptical is always last, trapezoidal delta is always somewhere in the middle, and trapezoidal swept is always first. However, in the airfoil cross-section row, fin shapes do not seem to matter.

Square	527	553	559	543
Rounded	545	548	588	529
Airfoiled	692	687	694	682

Fig. 20: This table compares the data of the three fin cross-section types. As seen in the bottom row, airfoil cross-section fins do not vary much in performance compared to the other fin cross-sections.

The pattern breaks, and all four fin profiles with airfoil cross-sections perform relatively equally, with a difference of only 12 feet between the lowest-performing and the highest-performing.

Why would an airfoil cross-section fin set subdue the effects of fin shape and surface area? our leading theory to this strange occurrence explains that due to the low speed of the rockets (the fastest one reaching just under 170 miles per hour), the amount of induced drag that each fin shape creates is negligible (since drag increases with the square of velocity).

To summarize our findings, while our hypothesis was proven correct in some areas, such as which fins would obtain the highest apogee, we were also proven incorrect in many areas, such as which fins would obtain the lowest apogee. Additionally, we were incredibly puzzled at the fact that all of the airfoil cross-section fins perform relatively equally, regardless of their surface area or profile.

Conclusions and Takeaways

To close, we dived into how different fin shapes, profiles, and cross-sections can impact a rocket's trajectory in this research project. We researched others' claims and thoughts on the subject, and then gave our own thoughts. We carried out an experiment that tested out various fin shapes and cross-sections, and our results seemed to communicate that our hypothesis was correct, with the exception of elliptical fins performing less than initially thought.

Through our analysis, we discovered how airfoil cross-section fins produced the best results out of the three given fin cross-sections. We theorize that this occurs because of the more streamlined shape of the airfoil cross-section – while all three cross-section types reach a maximum thickness of 0.125", meaning that they all have to displace the same amount of air, the forward airfoil cross-section stops less air molecules and does a better job in cutting through the air when compared to other cross-sections, which produces less drag. Additionally, the aft airfoil cross-section lets the separated air reconnect at the end of the fin easier. This explanation is similar to the reason why the swept trapezoidal fin shape produced the best results out of the four given fin shapes – its swept design collides with air molecules less violently than similar designs with lower sweep angles.

Something surprising about our test results was the lack of performance variation in airfoil cross-section fins. This also went against our initial hypothesis, and it was much more confusing to decipher an explanation for it than for the other findings that were contrary to our hypothesis. While we eventually concluded that while trapezoidal swept fins are generally the right choice, at low speeds and with an airfoil cross-section, it really does not matter what shape is chosen.

Among all of the claims we could find from others, none of them could accurately predict how airfoil cross-section fins would truly behave. We find this to be exceptionally fascinating, and we continue to find it strange how no one has ever come to these conclusions before. If anything, we believe this research project goes to show how valuable real-world experiments are compared to simply running simulations and making educated guesses, and how there are so many factors, both natural and artificial, that can contribute to drastically differing results in not just the study of aerodynamics or model rocketry but science as a whole.

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