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What is the best fin shape for a model rocket?

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What is the best fin shape for a model rocket

By Tim Van Milligan

Theoretically, the best fin shape for a rocket is an "elliptical fin shape."

I wanted to get that conclusion stated right here at the start.

Did you get that young student? I'm writing this for you. You came to the Apogee web site looking for information on "What is the optimum fin shape for a model rocket?", and if you want an answer, then write this statement down on your paper: "the elliptical shape is the optimum shape for a model rocket (**Figure 1**)." Please, write that down! It is an acceptable answer to the question. And now you can go play, your homework is done.

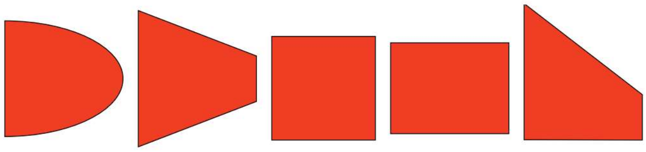

Figure 1: The elliptical fin (far left) is the best from a theoretical point of view.

In this article, I'll explain why it is the right "theoretical answer." But sometimes, theory runs into practicality, and that might not be the best answer if you are building a model rocket for an altitude competition.

The reason I'm writing this article is that grade school students come to the Apogee web site and download Apogee Technical Publication #16 "What is the Optimum Fin Shape for Altitude?" (https://www.apogeerockets.com/Rocket_Books_Videos/Pamphlets_Reports/Tech_Pub_16), and then send me an email asking that exact same question: "which shape is it?" I'm left shaking my head, wondering where the disconnect was, because they did download the report (I assumed they looked at it) which did tell them what shape was most likely the best.

It is obvious that they must not have understood the technical jargon in the report. Otherwise they wouldn't have to ask me what the answer was when it was already answered. So that is why I'm writing this article, to try to clarify what was in the Technical Publication #16 report in simpler language.

Why is the Elliptical Fin the Best Shape?

The reason the elliptical fin shape is best is that it produces the least amount of "induced drag."

Induced drag is a fancy aeronautical engineering term that means that the drag force produced is actually a result of something else happening. That means that two things are going on at the same time, and that the first thing causes the second thing to happen.

The two things are:

1. The Lift force on the fin is causing...
2. A drag force increase on the fin.

The lift force is the key factor. Lift is only created when the symmetrical airfoil is oriented at an "angle-of-attack" to the wind. That means the fin is tilted in the wind as it flies forward.

Why would the fin be tilted? That doesn't seem right, because don't we launch the rockets straight up?

Yes, we do launch the rockets straight up. And in a perfect world, the wind created over the fin as the rocket rises into the sky would strike the fin right at the leading edge (the very front edge of the fin). Half of the air would flow over each side as the paths of the flowing air were split by the leading edge. No lift would be created in such a situation. All you would have is a small drag force created from profile drag and skin friction drag.

But the atmosphere that the rocket flies

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through is not perfect. Little gusts of wind are always present.

What happens when the rocket flies through a small gust of wind is that the rocket sees a slight wind direction change. From the rocket's perspective, it is tilted very slightly relative to the wind flowing over the fin. This is called an "angle-of-attack."

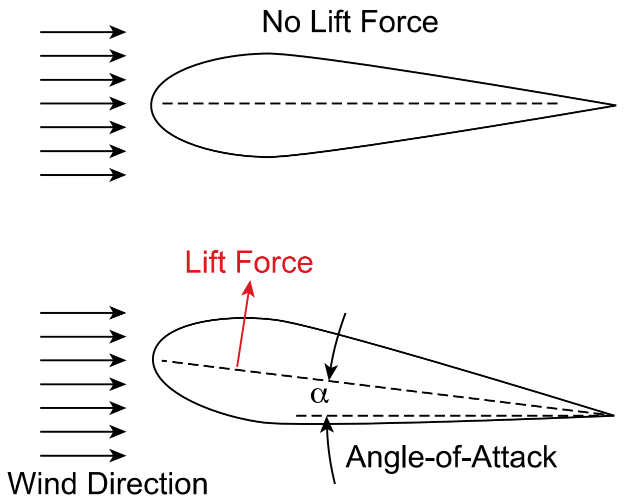

Figure 2: When a symmetrical airfoil is tilted relative to the air flowing over it, it generates a lift force.

As soon as the rocket is flying at an angle-of-attack (**Figure 2**), a lift force is created. And this is a good thing. We need this lift force to pull the rocket back to a straight path relative to the air flowing over it. In other words, if it were not for the lift force produced by the fins, the rocket would go unstable. Your rocket will not fly very high if it cartwheels across the sky.

Having a lift force to restore the rocket to a straight path is a needed in unguided model rockets. Even though the rocket may not be pointed perfectly straight up, it will still go higher than a rocket that doesn't have any fins.

Induced Drag occurs at the tips of the fins (the portion of the fin that is furthest away from the body of the rocket). What happens is that air flows around the corner of the tip edge from the underside to the top side (from the high pressure side to low pressure side). This is not the direction we want the air to flow. We just want the flow of air be parallel to the direction of the rocket. But since it flows around the tip, it now has a perpendicular flow direction. In mixes with the parallel flow closer to the rocket body tube, and causes a swirling motion (**Figure 3**).

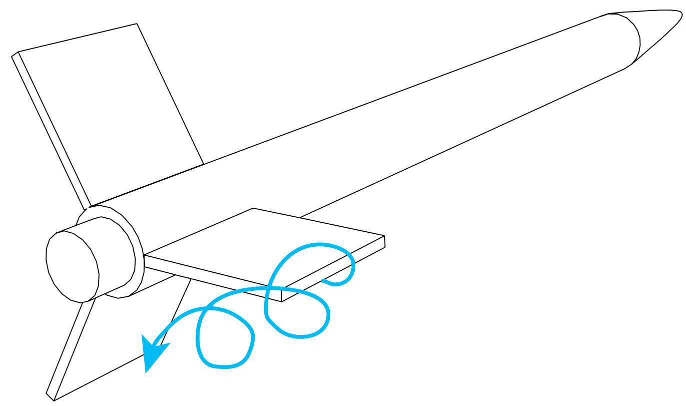

Figure 3: When lift occurs, air flows around the edge of the fin, from the high-pressure side on the bottom to the low pressure side on the top. This creates a tip vortex.

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Whenever you change the direction of a moving object, a force is needed. Remember Newton's First Law of Motion? "An object will move in a straight line unless a force acts to change the motion." The object in this case is the air molecules in the wind. Since the wind went from flowing parallel to the rocket to perpendicular to the rocket, a force must have acted on the rocket. We call this force "drag," because it slows down the speed of the rocket. And it has the special name of "Induced Drag" since it occurred because a lift force was the root cause of the air flowing from one side of the fin to the other. Without a lift force, there would be no extra drag force, and hence no induced drag.

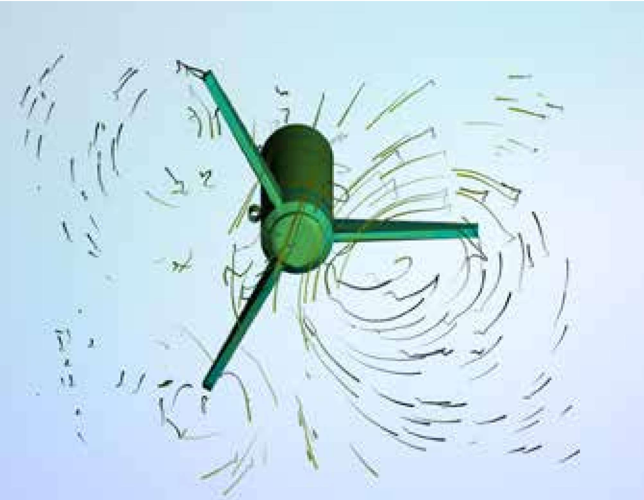

Figure 4: This rear-view from a computer simulation program shows how the air swirls behind the rocket off of the fin tips.

Why Does An Elliptical Fin Have The Lowest Induced Drag?

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. Figure 5 shows the span-wise distribution of the lift over the wing.

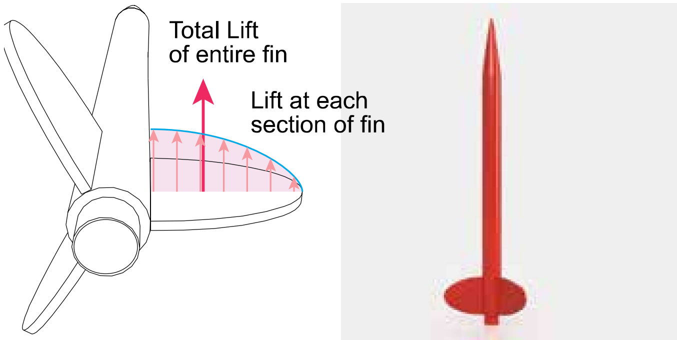

Figure 5: Span-wise lift distribution over an elliptical shaped fin. The summation of the lift forces (dark red line) is closer to the body than it is to the tip.

Because there is less lift near the tip of the fin, the difference in pressure (comparing the pressure on the top surface to that on the the bottom surface) is a lot lower near the tip. So less air flows around the tip. Hence, the induced drag force is lower. Lower drag means the speed of the rocket isn't being slowed down as much, so it can coast higher into the sky. That is why you can say that the elliptical fin has the most efficient shape.

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What is the worst shape fin?

The worst shape fin would have the highest induced drag. In other words, more air flowing around the tip edge of the fin. So making fins with an axe-head shape (shown in Figure 6) would be the worst, because most of the lift force occurs near the tip, creating more of a pressure difference between the upper surface and the lower surface. That causes more air to flow around the edge of the fin, which increases the induced drag.

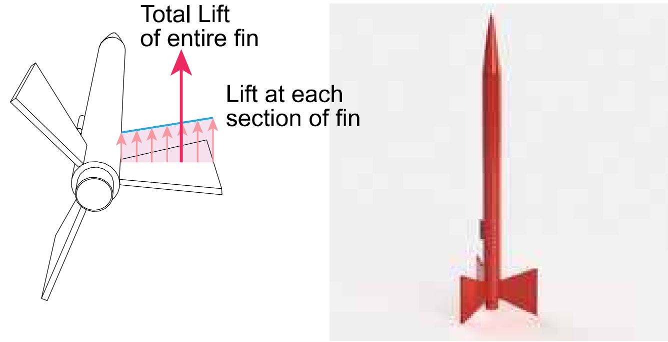

Figure 6: Axe-head shaped fins would have high induced drag because there is more lift near the tips, creating an even lower air pressure. This causes an even stronger tip vortex, and hence greater induced drag.

Induced drag is a real problem for aircraft that fly horizontally through the air. The reason is that it is always present, because a lift force is needed to hold the airplane up in the sky. That is why the aircraft makers add those curved-up winglets to the ends of the wing. They are meant to reduce the air flowing from one side of the wing to the other and thereby lowering the induced drag produced.

In contrast, in rocketry, we don't need lift to get us into the sky. That is the rocket engine's job. Moreover, we don't even want a lift force, except to keep the rocket stable. The lift comes and goes during the ascent, only present when the rocket hits a small gust of wind that changes the angle-of-attack orientation. Then the induced drag kicks in, and slows the rocket down. But once reoriented to a zero degree angle-of-attack, the lift goes away, as does the induced drag. At least until it flies through another little gust of wind from a different angle.

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What Else Affects the Altitude of the Rocket?

What we described to this point was just the fin shape all by itself. It is just one of the many variables that have to be considered when designing an efficient altitude rocket.

A bigger contributor to the drag is not the shape, but the cross section of the fin. In other words, if you sliced the fin in the middle (parallel to the body tube), and you looked at the edge - that is the cross section. The specific name for the shape of the cross-section is called the "airfoil."

The worst airfoil is a simple rectangular cross-section as shown in **Figure 7**. You can see the rectangular shape on the tip edge of the fin.

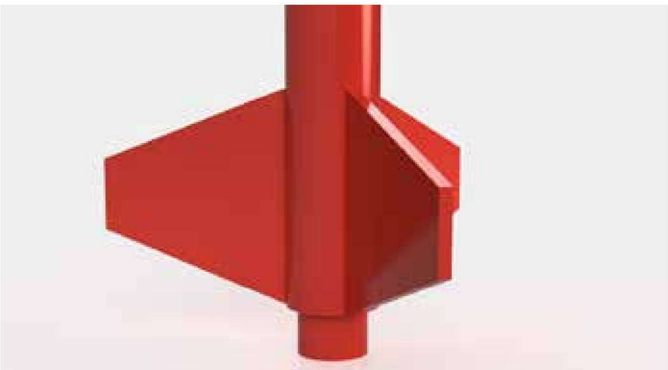

Figure 7: The cross section of this fin has a rectangular shape. You can tell by the sharp corners on the front and back edges.

The best airfoil for a typical low speed rocket like what most people fly has a symmetrical tear-drop shape. This means it has a rounded front edge, and reduces to a knife edge at the rear of the cross section (as seen in **Figure 2, Page 3**).

Switching from a rectangular airfoil to a symmetrical tear-drop shaped airfoil will drastically improve the performance of your rocket, which you'll see further along in this article.

Keep Your Airfoils Constant

Because we're typically using balsa wood for a construction material, the airfoils are sanded into the fins of your rocket. The question is, how good are you at sanding airfoils?

And this is where "What is the optimum shape of a fin" starts to get really complicated, and what I was trying to get into in Technical Publication #16. The airfoil needs to have consistent thickness-to-length ratio on both the root edge and the tip edge if you want mimic the span-wise lift distribution curve shown in **Figure 5, Page 4**.

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A consistent thickness-to-length ratio fin looks like **Figure 8.** This is a very hard airfoil to sand, because the fin tapers in thickness from the root edge against the tube to the tip end away from the rocket. This is called a "radial taper". In **Peak-of-Flight Newsletter #271** (https://www.apogeerockets.com/education/downloads/Newsletter271.pdf), you'll find plans to make a jig that will help you sand a radial taper into your fins.

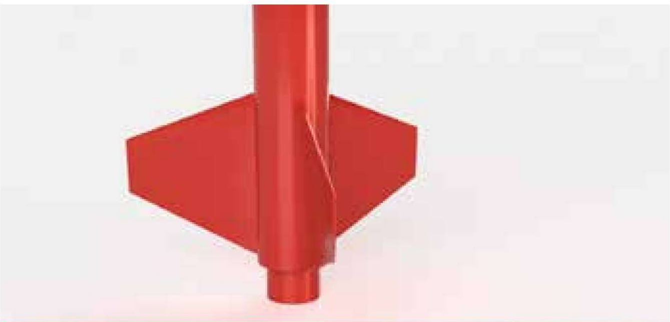

Figure 8: Optimized airfoil has a taper in thickness from the root (where it touches the tube) to the tip edge. It is thick at the root, and thin at the tip.

An easier airfoil to sand is shown in **Figure 9.** This is a constant thickness airfoil. But since the thickness-to-length ratio of the airfoil changes

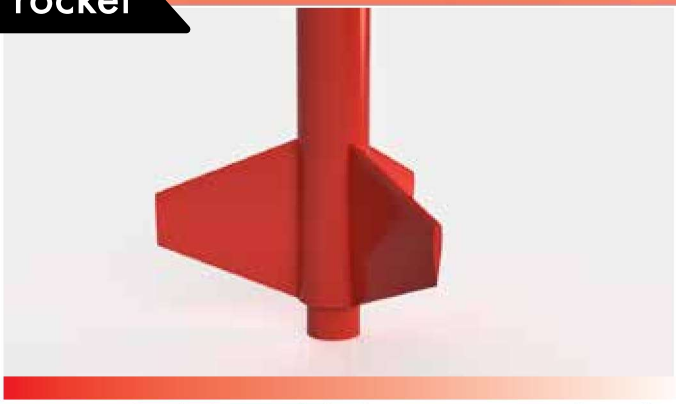

Figure 9: The thickness of the fin stays constant from the root edge (near the tube) to the tip edge. This in effect changes the airfoil from one edge to the other. While it is better than no airfoil (like Figure 7), it is not optimized like the one in Figure 8.

from the root to the tip, the airfoil changes too. This has the effect of moving more of the lift towards the tip of the fin. And with what we learned previously, this is like changing the fin to an axe-hammer shape, which is worse for induced drag.

However -- and this is important -- even though it moves the location of the average lift toward the tip edge, it is still worth sanding it into the fin, because the drag is still a lot lower than a fin with no airfoil (square edges). It is MUCH better!

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Adding the Fin to the Rocket

Up to this point, we've been concentrating primarily on the fin by itself. But when you add the fin to the rocket, the situation changes. The interaction of the rocket (the nose cone, the tube, and the joint between the fins and the tube) are additional variables that affect the overall drag of the rocket. So it isn't as simple as saying that the elliptical shape is the best in actual practice.

For this, we need to run some actual experiments to find out the best shape for a given rocket. I set up some Computational Fluid Dynamic (CFD) experiments on my computer, similar to the ones described in **Peak-of-Flight Newsletter #438** (https://www.apogeerockets.com/education/downloads/Newsletter438.pdf) using the Flow Design software. The results are shown in Table 1. Note that all these tests used fins with the same surface area, and they all had a rectangular airfoil (they weren't sanded; square edges).

From **Table 1**, you can see that the elliptical fin shape is low, but not the lowest. The Clipped Delta shape has a lower drag force at zero degrees angle-of-attack. And at 5° angle-of-attack, the Clipped Delta shape really beats the Elliptical shape. For some reason which I can't explain, the drag on the elliptical shape really increases. It may have to do with the rectangular airfoil cross-section. This is something I'm sure you'll want to test for yourself.

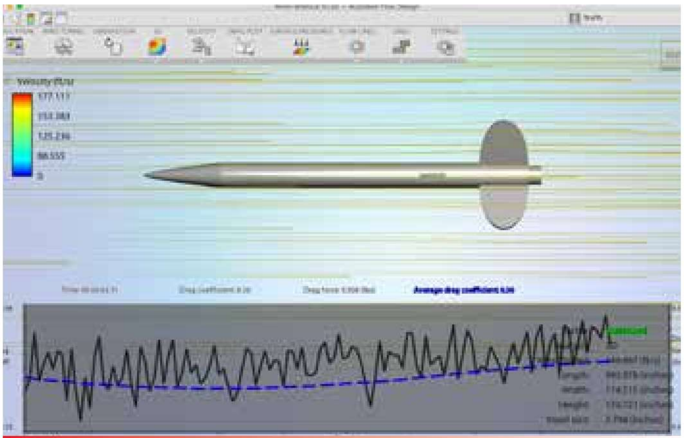

Figure 10: The virtual wind tunnel was used to estimate the drag on the Avion rocket kit, but with various fin shapes.

It looks as though the square fin has the least amount of drag. But this isn't the full story. When I set up the computer simulations, I tried to minimize the number of different variables in play during the simulations. But in the case of the square shape, the span (the distance from the root edge to the tip edge) had to be reduced in order to make a square shape. All the other fins stick out the same distance from the

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Angle-of-Attack		Elliptical	Trapezoidal	Square	Rectangular	Clipped Delta
0°	Drag Force	9.508	10.690	9.023	11.337	9.357
5°	Drag Force	12.052	12.262	10.567	11.685	10.907

Table 1: Drag Force on various fin shapes when attached to rocket. Rocket was scaled up 10X and run in the software at 100mph.

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rocket. It is better to use the rectangular shape for comparison, because it has the same span as the elliptical fin. In this case, the rectangular fin shape is the worst among those tested.

The next variable, which you'll see has far more impact on the drag and that I mentioned in Technical Publication #16, is the airfoil section sanded into the fin. In this case, all the fins had the same shape (a trapezoid that is used on the Avion rocket kit (https://www.apogeerockets.com/Rocket-Kits/Skill-Level-1-Model-Rocket-Kits/Avion).

Angle-of-Attack		Rectangular Airfoil	Non-Tapered Airfoil	Tapered Airfoil	Thin Plate
0°	Drag Force	11.337	4.955	3.463	3.435
5°	Drag Force	11.685	7.712	7.030	6.783

Table 2: Estimated drag forces for fins with the same shape, but different airfoils.

The Rectangular shape, which is the unsanded fin with square edges (shown in **Figure 7, Page 6**), is the the worst. You don't want to make a fin like this, unless you are going for aesthetics. You'll notice that almost all the models on the Apogee web site have square edges, but it is because I like the look of them in the pictures. The edges "pop" out and are highly defined. For flight, you should always try to make better airfoils.

If you sand a regular airfoil into the fin like shown in **Figure 9,Page 7**. The drag drops dramatically. As mentioned, this isn't a hard airfoil to sand into the balsa fin. Note that it has less than half of the drag of an Elliptical shape with square edges on the fins (from **Table 1**).

The tapered airfoil (as seen in **Figure 8**) is even better. This is a hard fin to make, but it is worth the effort.

The last fin in **Table 2** is the thin plate. This is shown in **Figure 11**. It is really the same airfoil cross section as shown in **Figure 7**, **Page 6**. With the only difference being the thickness of the wood that you start with. The key here is that the thinner the fin, the less drag it will have.

Competition modelers often use very thin sheets of fiberglass or carbon fiber to make high performance fins. They need the stiffness, because they are very susceptible to fin flutter. If the fin begins to flutter, you'll hear a buzzing sound. In this case, the drag goes up exponentially, and very often the fins will snap completely off the rocket. For this reason, they aren't typically used on rockets where large fins are needed for stability. The tapered airfoil, shown in Figure 8, uses the natural thickness of the fin to prevent fin flutter.

The disadvantage of thin plate fins is that they generate less lift force than fins with a real airfoil sanded into them. What this means is that the rockets will take longer to correct their flight path if they hit a gust of wind. Therefore the rocket will spend a longer amount of time at an angle-of-attack, and will have higher drag. If you do use thin plate fins, you better make sure they are absolutely straight on the rocket, and that you get a

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good high-speed take-off (such as using a piston launcher). You want to try your best to ensure a straight flight so that the rocket doesn't have to get into an angle-of-attack situation.

Optimizing Your Fins For Altitude

Isolating the variables that go into making an optimized fin, you want:

1. A small fin span - "stubby fins"
2. A symmetrical (teardrop) shaped airfoil
3. A thin or spanwise tapered piece of wood.
4. An elliptical or trapezoidal shaped fin

The variable we didn't talk to much about is the span of the fin. While you want stubby fins to keep the drag low, the limiting factor is the stability of the rocket. The fins have to stick out far enough into the airstream to generate lift. You'll want to make sure you check your RockSim simulations to ensure the CP with the short stubby fins you have is enough to keep the rocket stable. The one-caliber stability rule is a good one to follow to make sure your fins are big enough to keep the rocket stable. For stubby fins, a good tip is to sweep them aft, in order to help move the CP of the rocket rearward in order to get the stability margin where you need it. Notice that the "Clipped Delta" shaped fin from Figure 1 has the same dimensions, like root chord, tip chord, and span lengths as the trapezoid. The only difference is that the leading edge is swept further aft.

The elliptical or trapezoidal shaped fin isn't really that critical in the grand scheme of things. You'll remember, as soon as we attached the fin to the rocket, and the other components on the rocket interacted with the flow of air over the fin, it turns out that the clipped delta was a better shape. It really is going to depend on the entire rocket you have that will determine the best shape for your rocket.

Speed Changes Everything

What we discussed in this newsletter was the best shape for a "model rocket." Model rockets typically fly around 100 to 200 mph. When you start going significantly faster than this, like you might in high thrust or high power rockets, then you could get into compressible airflow. In that case, you can throw out a lot of what was discussed here. Speed changes everything. This is why jet airplanes don't use elliptical fins. They use a swept trapezoid shape.

Conclusion

Hopefully, you'll come to the same conclusion that I have reached. Optimizing your fins is a lot harder than just picking a fin shape. It is much more complex than that.

About The Author:

Tim Van Milligan (a.k.a. "Mr. Rocket") is a real rocket scientist who likes helping out other rocketeers. He is an avid rocketry competitor, and is Level 3 high power certified. He is often asked what is the biggest rocket he's ever launched. His answer is that before he started writing articles and books about rocketry, he worked on the Delta II rocket that launched satellites into orbit. He has a B.S. in Aeronautical Engineering from Embry-Riddle Aeronautical University in Daytona Beach, Florida, and has worked toward a M.S. in Space Technology from the Florida Institute of Technology in Melbourne, Florida. Currently, he is the owner of Apogee Components (http://www.apogeerockets.com) and also the author of the books: Model Rocket Design and Construction, 69 Simple Science Fair Projects with Model Rockets: Aeronautics and publisher of the Peak-of-Flight Newsletter, a FREE e-zine newsletter about model rockets. You can email him by using the contact form at: https://www.apogeerockets.com/Contact.