PEAK OF FLIGHT NEWSLETTER

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15 WAYS TO INCREASE THE STABILITY OF YOUR ROCKET

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15 Ways to Increase the Stability of Your Rocket

By Tim Van Milligan

"Where should the balance point be on my model rocket?" This is a common question we get all the time from modelers, and implies that the person wants to make sure that their rocket flies straight and true when they launch it. They don't want it to go unstable.

But at the same time, it indicates that they are overlooking some important concepts about rocket stability and safety risks. In this article I want to review the factors that determine if a rocket will be stable, and then give some some general advice on what you should do if you modify a rocket kit.

Basics of Rocket Stability

Understanding the principles of rocket stability and how to achieve it is essential to launch a rocket that flies high and true. The basic parameters of stability are the Center-of-Gravity (CG) and the Center-of-Pressure (CP). Each of these are a "point" on the rocket. And it is the location of the two points (relative to each other) that determine if a rocket will be stable when flown.

The basic concept of stability is that the Center-of-Gravity must be more towards the nose than the Center-of-Pressure. If this is true, the rocket will likely fly straight and predictably. If the Center-of-Pressure is more towards the nose than the Center-of-Gravity, the rocket will fly unstable and erratically.

"Keep the CG in front of the CP." That is the law of physics as applied to rocketry.

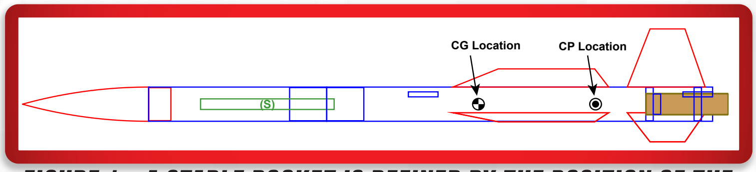

FIGURE 1 - A STABLE ROCKET IS DEFINED BY THE POSITION OF THE CG AND CP. THE CG MUST BE MORE FORWARD FOR THE ROCKET TO BE STABLE.

The Center-of-Gravity:

The Center-of-Gravity (CG) of a rocket is the point where the rocket's weight is balanced. It is easy to find, as you just literally balance the rocket on your finger. When the rocket stays put, you have found the CG! It should be noted that when you are trying to locate the CG point, ALWAYS put in a new rocket motor into the model! Preferably, it should be the biggest motor you intend to fly in the rocket so the heavy motor shifts the CG point further rearward.

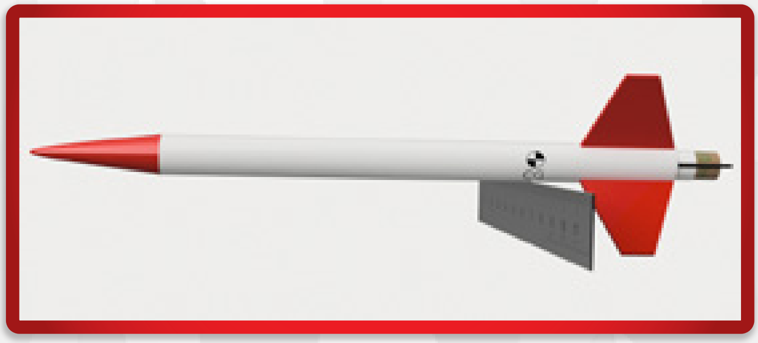

FIGURE 2 - TO FIND THE CG, YOU SIMPLY BALANCE THE ROCKET ON A RULER'S EDGE.

The most important aspect of the CG is where the rocket rotates; it will ALWAYS spin around the CG point. So another way to find the CG is to simply toss it in the air, and find the point in the middle where it spins around.

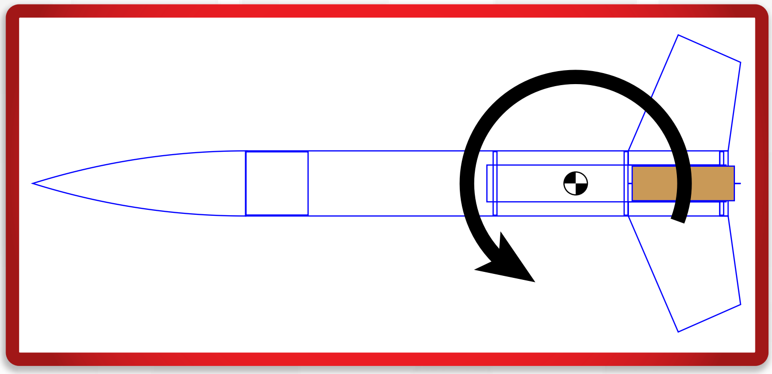

FIGURE 3 - A ROCKET WILL ALWAYS ROTATE WITH THE CG AT THE CENTER.

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Center-of-Pressure (CP)

As the rocket moves through the air, forces are generated on the vehicle. These are called “aerodynamic forces” because they are only present when air is flowing over or around the rocket. When you stop the airflow, the forces go away completely.

There are only two aerodynamic forces created: Lift and Drag. I’m sure you’ve heard of them. Drag is the force in the opposite direction that the rocket is traveling. So if the rocket is moving upwards, then drag is downwards. (See Figure 4)

Lift is perpendicular to the direction of travel of the rocket. If the rocket is moving upwards, then Lift is produced to the horizontal.

The thing is that every component part of the rocket that is exposed to the air flowing over it produces both lift and drag. Nose cones produce lift and drag. Fins produce lift and drag. So do body tubes and launch lugs. So if you look at only the forces on the rocket, you’ll see they are scattered everywhere on the surface.

Forces can also be added together. For example, say you stepped on a scale and it reads 150 lbs. That is a force. Then you pick up a heavy box, which weighs 20 lbs. The forces are added together, and you will see the scale will indicate 170 lbs of weight.

The same thing happens in rocketry: the lift and drag forces are added together. We’re going to take all the little forces that are created all across the rocket and add them up. We get a total force, and we also get a “point” on the rocket where that total force is located. The point is called the “Center of Pressure.” It is where the aerodynamic forces balance. In other words, there is just as much lift and drag in front of the point as there is behind it.

Now we have the two points on the rocket: the Center-of-Gravity, where the rocket will spin around, and the Center-of-Pressure, where we say that all the aerodynamic forces are concentrated.

As we said, if the Center-of-Gravity is forward of the Center-of-Pressure, the rocket will fly stable. If the CG is behind the CP, the rocket is unstable.

It is the relationship between the location of the points that is important. The further forward the CG is from the CP point, the MORE stable the rocket will be. If the points are close together, then we say the rocket is “LESS” stable.

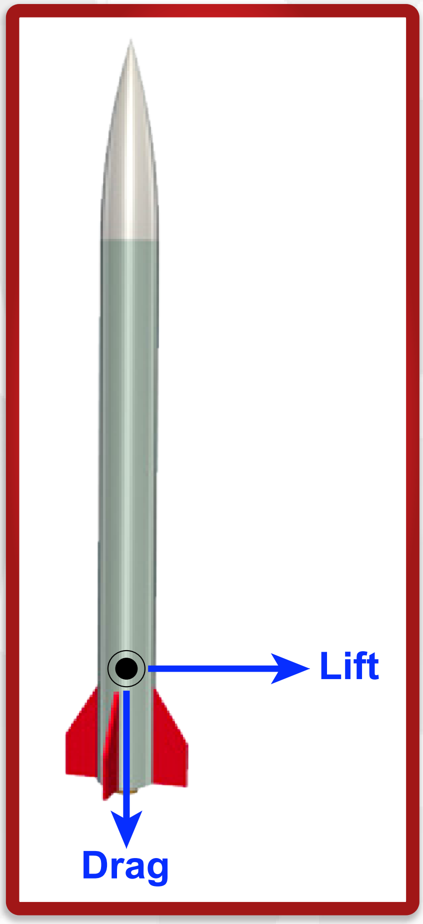

FIGURE 4 - THE SUM OF ALL THE LIFT AND DRAG FORCES ARE CENTERED AT THE CP OF THE ROCKET.

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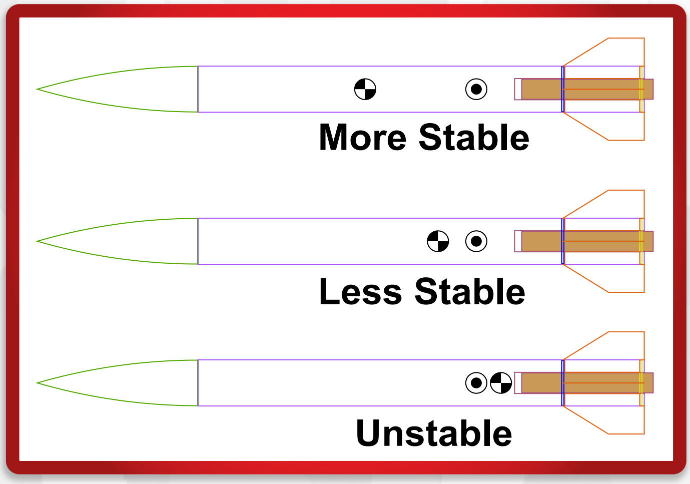

FIGURE 5 - THE DISTANCE THE CG IS FROM THE CP DETERMINES HOW MUCH STABILITY THE ROCKET HAS.

More Stable Compared to Less Stable

What does it mean to be "more stable" compared to being "less" stable? It is relative, but you could say that rockets that are "more" stable will react quicker to changes in the aerodynamic forces applied to the rocket. You will notice that it spins quicker.

So for example, the rocket is flying upwards and a sudden gust of wind hits the left side of the rocket. It wants to push the rocket sideways towards the right. But what happens is the Lift Force on the rocket also increases, and this causes the rocket to rotate. It could rotate in a clockwise or counter-clockwise direction. But by definition, if the rocket is "stable," the increase in the lift force will cause a rotation that points the nose into the wind.

In a "more" stable rocket, the rocket will quickly react to the wind, and eventually point the nose into the wind. In a "less" stable rocket, it will still point the rocket into the wind, but it does it more slowly. So in breezy conditions, a more stable rocket is going to swing around and arc into the wind. A "less" stable rocket will eventually get to the same orientation, but will take longer to do so.

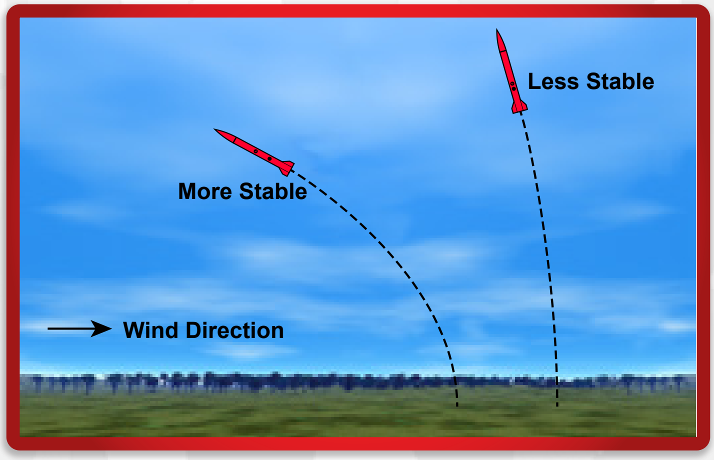

FIGURE 6 - A "MORE" STABLE ROCKET WILL ARC INTO THE WIND FASTER.

What you'll notice is that a "more" stable rocket will typically fly horizontally into the wind, where a "less" stable rocket will straighter up.

Knowing this, most people assume that a "less" stable rocket is optimal because it goes higher in windy conditions. But there are some situations where having the CG and the CP points too close together (which is the definition of a "less" stable rocket) is a bad thing.

Here is where it gets complicated…

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How Do You Calculate the CP location?

The most important question you have to ask is "How do you calculate the CP location?" Since you can't just balance the rocket on your finger like you can do with the Center-of-Gravity, it is more complicated to find the balance point of the aerodynamic forces. It is not easy, and it is critically important.

The first method modelers developed to find the CP point was called the "Cardboard Cut-out Method." See Peak-of-Flight Newsletter #18 (https://www.apogeerockets.com/education/downloads/Newsletter18.pdf) for how it works.

Unfortunately, the Cardboard Cut-out Method estimates that the CP point is really far forward on the rocket. To compensate for this, a lot of nose weight has to be added to move the balance point in front of the CP point.

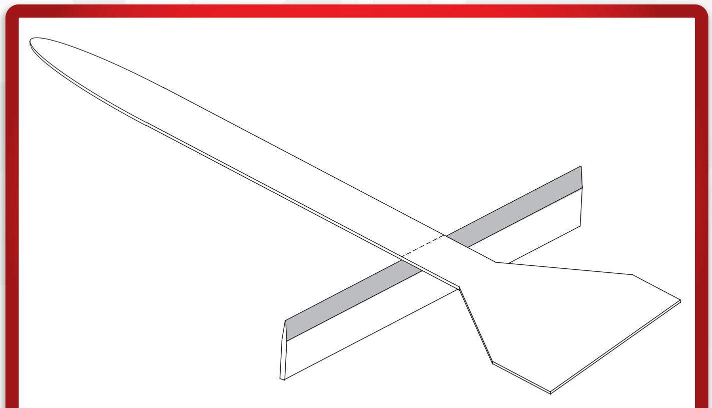

FIGURE 7 - THE CARDBOARD CUTOUT METHOD PUTS THE CP TOO FAR FORWARD ON THE ROCKET, WHICH MAKES IT OVERLY CONSERVATIVE.

In real life, the CP is further back on the rocket, but we've moved the CG forward by adding nose weight. In essence, we've made the rocket "more" stable, which results in more weathercocking and lower flights.

In 1965, Jim Barrowman produced a report that gave a mathematical way of calculating the CP position on the rocket. It is sometimes called the "Barrowman Method," or the "Static Stability Equations." Compared to the Cardboard Cut-out Method, the CP location is further back on the rocket.

These equations are still used today by many modelers, because they seem to work fine. Additionally, they have been slightly refined in the RockSim Method (see: Peak-of-Flight Newsletter #238 at https://www.apogeerockets.com/education/downloads/Newsletter238.pdf) to try to get a more accurate location of the CP point on the rocket.

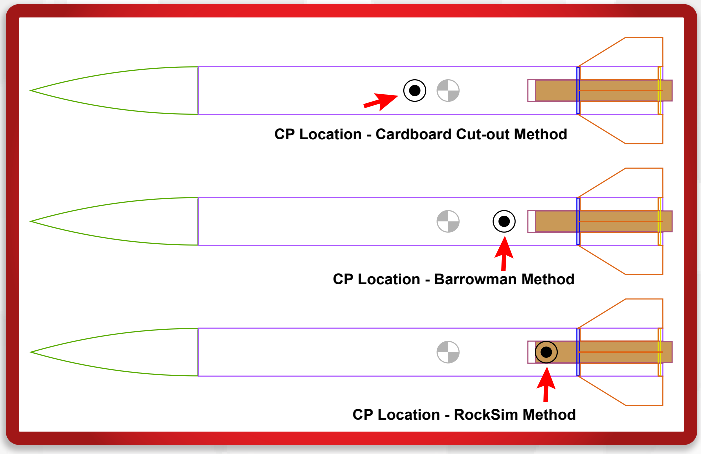

FIGURE 8 - THE CP LOCATION WILL BE IN A DIFFERENT SPOT DEPENDING ON WHICH METHOD YOU USE.

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As you might surmise, there is still some ambiguity in the exact location of the CP point on the rocket.

This is important, because you have to ask yourself the question: “What if the actual CP point is further forward than where we calculated it to be?”

If the CP point is closer to the CG, the rocket will be less stable. We might be able to live with that. But in a worst case situation, if the CP is actually ahead of the CG point, then the rocket will be unstable. It will do cartwheels in the sky when we launch it. This is totally unsafe, and something we cannot tolerate.

Because we are uncertain of the exact location of the CP, we have to do something to make certain that the rocket will still be stable when launched. What we do is artificially move the CG point further forward on the rocket to compensate for not knowing the exact CP location. That will make the rocket more stable.

But how much further forward? Based on historical experience, a good rule of thumb is to have the CG position about one tube diameter forward of the CP location. So if your rocket is 1 inch in diameter, you want to see the CG at least 1 inch in front of the CP.

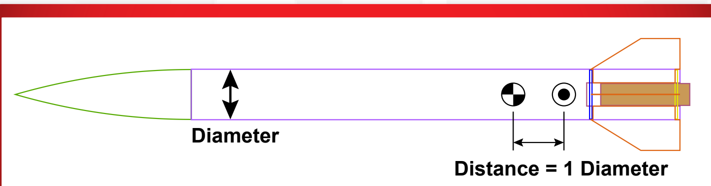

FIGURE 9 - SINCE WE ARE UNCERTAIN WHERE THE CP ACTUALLY IS, LET’S TRY FOR A SITUATION WHERE THE CP IS ONE TUBE-DIAMETER BEHIND THE BALANCE POINT. THIS IS CALLED “1-CALIBER STABILITY” OR “STATIC MARGIN = 1.0”

If it is a 2 inch diameter tube, then the CG should be about 2 inches in front of the CP.

This “1-caliber” static stability safety margin (as it is called), has stood up very well for rocketeers. It isn’t perfect, but is good enough from a safety standpoint. The rocket absolutely has to be stable before we launch it, and this 1-caliber safety margin gives us the confidence that it will be stable.

You can get this information in the RockSim software from Apogee. I always recommend using the RockSim software when designing a rocket, because it is going to instantly give you updates on the stability of the design as you make any changes. When you add a fin or move it around, RockSim will instantly tell you where both the CG and the CP are. From that, you can make a decision if your rocket will be stable when flown.

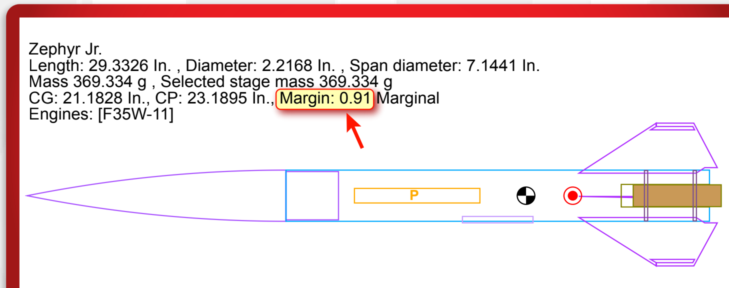

FIGURE 10 - ROCKSIM LISTS THE “MARGIN”, WHICH IS THE DISTANCE THAT THE CG IS IN FRONT OF THE CP, MEASURED WITH RESPECT TO THE TUBE DIAMETER.

Also, use the RockSim method for determining the CP location; based on our experience, it is the most accurate. See the references for more information about this.

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What Actually Happens When a Rocket Is Launched?

What we discussed up to now is called “Static Stability.” By using the word static we assume that nothing changes when the rocket is launched. In other words, the CP location doesn’t move; it is fixed in place.

In actuality, both the Center-of-Gravity, and the Center-of-Pressure points do shift around during flight. They don’t stay fixed in one location. This is called “dynamic.”

The Center-of-Gravity typically shifts forward during flight as the rocket burns off propellant. In effect, the back end of the rocket gets lighter in weight. If the back gets lighter, then the overall balance point of the rocket must shift forward.

This is actually good news, because the CG shifting forward means the rocket is becoming more stable as it takes off.

You might have seen a rocket take off and immediately go unstable as it leaves the launch rod. It may have spun wildly around and around, and then suddenly it takes off in one direction. What happened here is that the CG shifted further forward as the back end of the rocket got lighter, and it finally reached the point where it was ahead of the CP and became stable.

The CP can also shift during flight. It moves when the Lift force on the rocket changes. This could be due to wind, or something like fin flutter (bending of the fin).

Which direction does the CP move? Unfortunately, it most likely moves forward in response to changes in forces. For example, if a fin breaks off of your rocket, there is less lift force near the back, which moves the balance point of the aerodynamic forces further forward. If the CP shifts forward of the CG, we now have an unstable rocket. That is very bad.

Dynamic Stability is very complicated, but if you generally follow the guideline of 1-caliber stability, your rocket should fly fine because the CP doesn’t usually shift too much unless the rocket is at a really high angle-of-attack. If you’d like to learn more about dynamic stability, there are references at the end of this article.

Designing a Stable Rocket

Now that we have a basic understanding of stability, we can make some recommendations on how to make a rocket more stable.

There are some parts on a rocket that have a stabilizing effect, and others that will destabilize the rocket. So when designing a rocket, keep in mind that some parts will help make it more stable. For example, these parts help make the rocket more stable:

- Nose Cones
- Fins (behind the CG of the rocket)
- Transitions where the smaller diameter is oriented toward the front of the rocket

These parts make the rocket less stable:

- Fins (forward of the CG)
- Transitions or Boattails where the smaller diameter is oriented toward the aft end of the rocket

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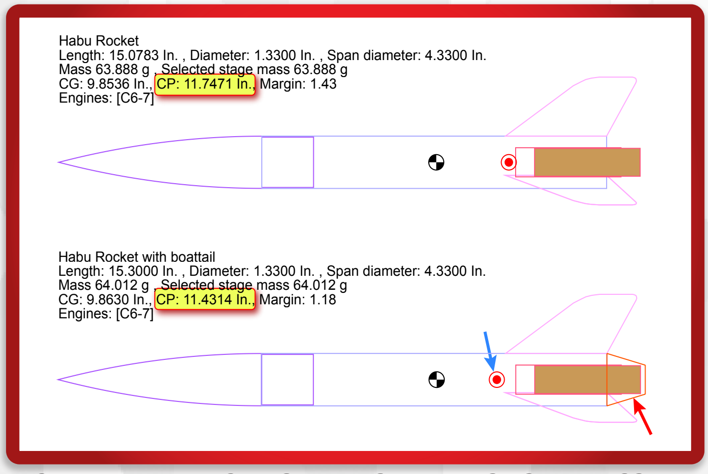

FIGURE 11 - ADDING A BOATTAIL ON THE BACK OF THE ROCKET MOVES THE CP FORWARD, MAKING THE ROCKET LESS STABLE.

These parts are neutral and have little contribution to the stability of the rocket:

- Body tubes
- Launch lugs (rail buttons, rail guides)
- Paint

Rocket Ideas for Increasing Stability or Preventing Instability:

By far, the biggest contributor to increasing the stability of the rocket are the fins and their placement on the rocket. Here are some ideas for making your rocket more stable:

1. Increase the number of fins - each fin added to the tube will help move the CP further back. For example, a four fin rocket will be more stable than a three fin rocket.

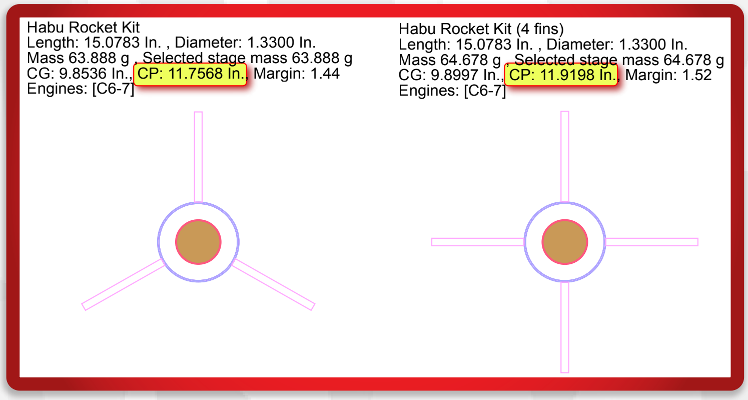

FIGURE 12 - ADDING FINS MOVES THE CP REARWARD, INCREASING THE STABILITY OF THE ROCKET.

2. Increase the fin area - also note, that a wider fin that sticks out further from the body tube will provide more stability than one that has a longer root chord where it attaches to the tube. This is the FIRST choice for increasing the stability, because it has the greatest effect on the rocket.

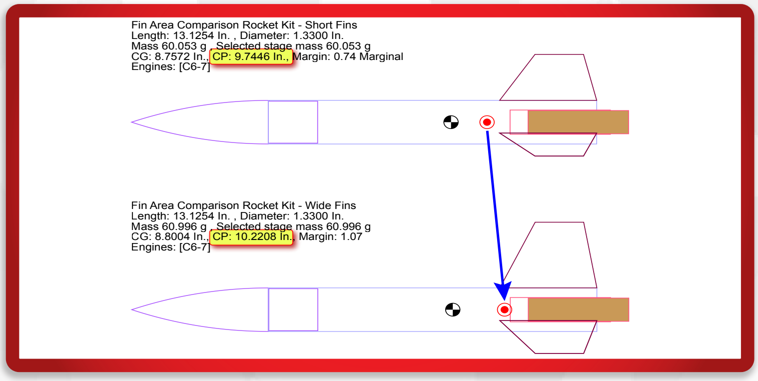

FIGURE 13 - MAKING THE FINS LARGER HAS A SIGNIFICANT IMPACT ON THE CP LOCATION.

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3. Sweep the fin backwards - If two fins have the same area, the one that is angled backwards will provide more stability. Avoid sweeping the fins forward, as that is like moving them higher up on the tube.

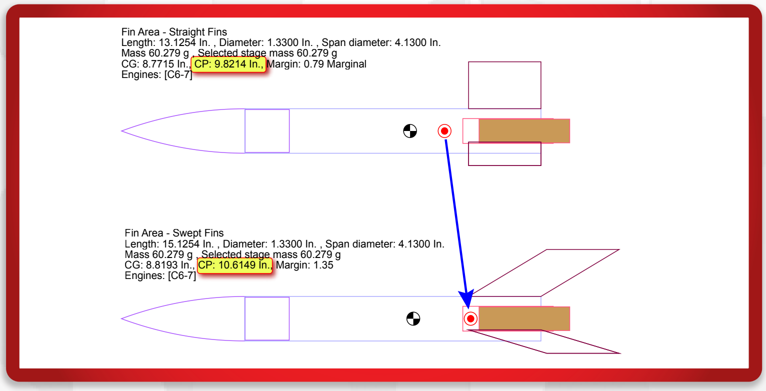

FIGURE 14 - SWEEPING THE FINS REARWARD MOVES THE CP BACK, INCREASING THE STABILITY OF THE ROCKET.

4. Move the fin as far back on the tube as possible. This will move the CP rearward as well. Avoid putting fins on the rocket in front of the CG point. This is highly destabilizing and should be avoided whenever possible.

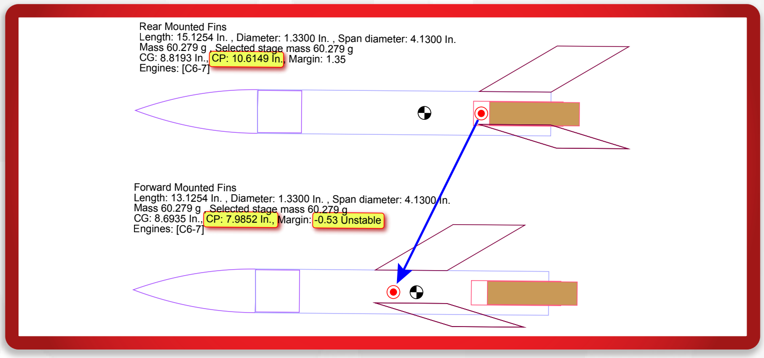

FIGURE 15 - PLACING THE FINS FORWARD ON THE TUBE IS DESTABILIZING. IN THIS CASE, THE ROCKET GOES UNSTABLE.

5. Tilt the fins on the tube, so that the canted fins will cause rotation of the rocket. This gets into dynamic stability, but a spinning rocket is far more stable than one that doesn't rotate around its long axis.

FIGURE 16 - CANTING THE FINS ON THE TUBE CAUSES THE ROCKET TO SPIN, INCREASING ITS STABILITY.

6. Airfoil your fins. This will make them more efficient at creating lift. And at the same time it will reduce the drag. The effect is more stability because the rocket reacts quicker, and also higher flights.

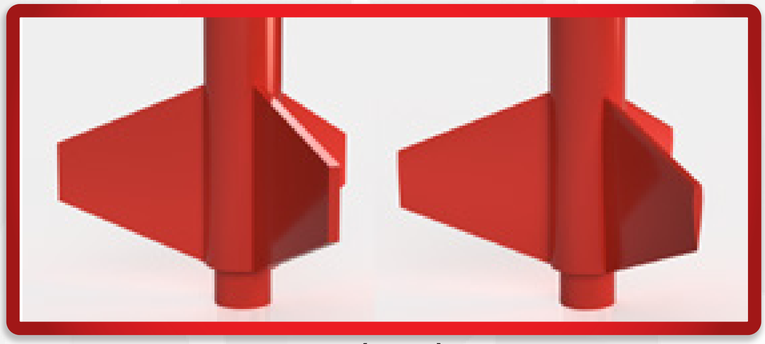

FIGURE 17 - AIRFOILED FINS (RIGHT) ARE MORE EFFICIENT AT GENERATING LIFT, SO THEY ARE STABILIZING.

7. Choose a higher thrust rocket motor. This will cause the rocket to take off faster, which increases the lift forces created by the fins. You can compare motor names, such as C6 versus the C16. The number after the letter is the average thrust of the motor. So a higher number will push the rocket faster off the launch pad.

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8. Speaking of speed, use a long launch rod. The longer the rod, the higher the speed of the model when it takes off. Speed is your friend for increasing the stability of your model.

9. Keep the back end of the rocket as light as possible. Be careful how much epoxy or glue you use for the fin fillets. Also avoid using heavy engine retainers or adding any internal structure. The added weight moves the CG rearward and closer to the CP of the rocket. If possible, use less dense materials like balsa wood for fins instead of plywood or plastic. If you're a real expert, you'll look for tricks to make parts in the rear of the rocket lighter weight, like using foam-core for fins and centering rings. There are all sorts of building techniques that you can use to make strong parts that are also low weight.

10. Secure components inside the rocket so they can't shift rearward. When a rocket takes off, many items inside the tube like to shift downward, which moves the CG back towards the CP. Parachutes and wadding shift all the time. You should worry most about heavy payloads like altimeters and batteries. Shake your rocket before launch. If you can hear anything rattling around or shifting position, try to brace it so it can't move. I like to use sponge foam because it is lightweight and can conform around payloads in the rocket without damaging them.

11. Build with precision in mind. For example, make sure all the fins are attached perfectly straight. If one fin is crooked, it will unbalance the forces on the rocket and could cause the rocket to go unstable. Use fin jigs whenever possible to make sure you attach your fins perfectly straight.

Figure 18 -Use a fin alignment jig when installing the fins to make sure they are on perfectly straight.

The same goes for your engine mount. Make sure it is concentric in the tube and is parallel with the axis of the tube. A canted motor mount is rare, but is something you should check.

12. Choose fin materials that are very stiff so that they don't flutter and buzz. When fins flex and flap back and forth, they generate lift forces that aren't optimal for the direction of flight and will cause instability. Additionally, they cause a lot of drag that will slow your rocket down. In extreme cases, the fins will shred from the rocket and then you don't have any restoring forces to provide stability.

13. Avoid putting heavy or bulky objects on the side of the rocket. An example would be a large or heavy camera. This will cause what is called pitch-roll coupling. The extra drag on one side of the rocket will cause the rocket to turn in that direction. Once it turns, the fins on one side of the rocket will start to generate a lot of lift, but in a direction that causes the rocket to roll. There will be an imbalance that will last the entire flight. The rocket

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will probably corkscrew and won't fly as high as a rocket that goes straight.

14. Make the rocket longer. A longer rocket will move the CG further away from the fins. Yes, it will add weight to the front of the rocket, but you get an efficiency factor for the weight you add when it increases the length. This is much more preferred than adding nose weight. As an aside, many people ask if adding an ebay or payload tube to the front of the rocket would be ok. I say "GO FOR IT!" This makes the rocket longer, and that will always make it more stable. It will never make the rocket go unstable.

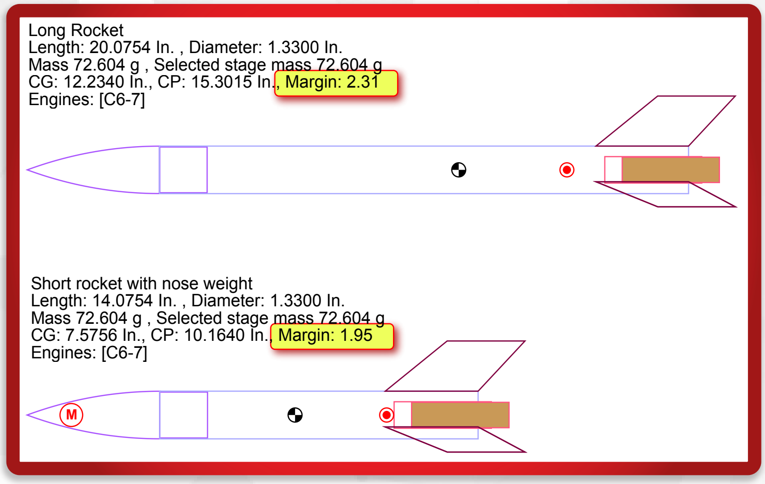

FIGURE 19 - THE STATIC MARGIN IS GREATER WITH A LONG ROCKET VERSUS A SHORT ONE, EVEN IF THEY BOTH WEIGHED THE SAME.

15. And as a last resort, you can add nose weight such as putting modeling clay in the nose, or adding washers to the base of a balsa nose cone. This is my least preferred method of fixing stability issues, because dead weight is just that, dead. It takes a lot of weight to move the CG forward if it is a short rocket.

Additionally, adding weight to the rocket increases the amount of damage it could cause should it crash. A heavy rocket will always cause more damage than a lighter weight one. In my mind, this is a safety issue, so I will always advise against adding extra weight if you do have other options. And as this long list infers, you have a lot of options to make your rocket more stable that don't involve adding nose weight.

It should be noted that if you do have heavy components that need to be in the rocket, such as batteries for your electronics or a payload like an altimeter, tracker or a camera, put them as far forward in the rocket as you can. Many people will stuff them inside the nose cone because that is as far forward as you can get. This isn't adding extra weight, but shifting the current weight inside the rocket to increase stability.

Conclusion:

What I've found from experience is that most of the people that ask where the CG point should be on the rocket have modified the rocket in some way from the original design. Usually, they over reinforced the rocket by adding thick epoxy fillets, and made it into a heavy pig. Now they want to get the rocket back to being stable, and they want to do that by adding more nose weight.

In my opinion, intentionally adding weight to a rocket is primarily for adjusting the expected altitude of the rocket. For example, a lot of TARC teams will put in weight to lower the height that the rocket will achieve. But I don't like adding weight to adjust the stability of the rocket. That is a "last resort" technique for stability.

In reality, it may not always be necessary to add extra weight to your rocket. Did you check the stability by comparing the new balance point (after modifying the rocket) to the CP position predicted by RockSim? If you don't know what the CP position is, then you could be adding dead weight that really isn't needed.

That is why it is my policy to never put the CG point on the web pages of the rocket kit. We always give the CP point so you can make a proper comparison. I don't want you to have to add weight that isn't required. Most of the time, it isn't required because nearly all kits are designed with greater than 1-caliber stability. So they are likely to be a little bit tolerant of builders that apply heavy fillets on the back end.

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Other stability topics can be found at: https://www.apogeerockets.com/Peak-of-Flight?pof_list=topics&#Rocket_Stability

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 an 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.