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Why Do Tall Rockets Go Unstable?

By Tim Van Milligan

David Mathes writes:

"I read with interest the Rocksim vs Barrowman article (www.ApogeeRockets.com/education/downloads/Newsletter238.pdf). I've had this goal of building a tall rocket for some time. So the comments regarding even the 1/70th model of the Saturn V were of interest.

*With higher strength materials from kevlar and Blue Tube, to carbon fiber with epoxies, building a tall rocket seems doable. However, at length/diameter ratios of 100 or 1000 to one, other factors may come into play such as vibration, the requirement for a second *hull* to form an inner structure, and the distribution of forces along the length, especially any shear. Small fins will be added the length of the rocket. The weathercocking issue you cited recently concerns me too.*

For high length/diameter ratio rockets, any comments on what may be the limitations in Rocksim or Barrowman."

This is a good question that seems to pop up every now and then. And I like to see people ask these kind of questions, because it shows that there is a desire to learn more about rocketry and how to make better rockets. And it gives me something to write about, so please keep those questions coming.

There was a great article by Robert Galejs called "Wind Instability, What Barrowman Left Out" that describes the situation with very long rockets. It can be downloaded at http://projetosulfos.if.sc.usp.br/artigos/sentinel39-galejs.pdf. I highly recommend that you read it, as he does go through the math involved and points out the problem with long rockets.

Basically, it comes down to the length of the tube itself, and the aerodynamic forces acting on such a tube.

In 1966, Jim Barrowman assumed that rockets were going to be flying at very low angles-of-attack. When you make that assumption, the forces on a body tube are so small that they can be neglected. That simplifies the equations greatly.

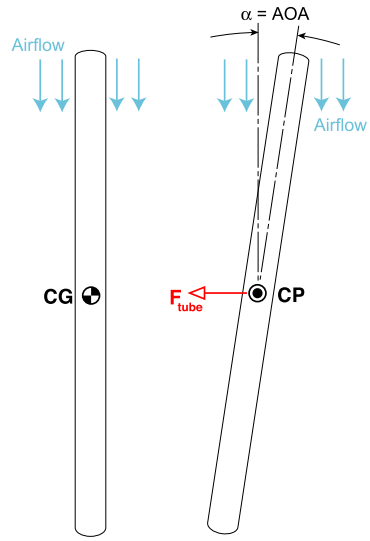

Figure 1: When a tube flies straight up, there are no forces acting on it. But when at an angle-of-attack (AOA), there is a force that is created.

In Figure 1, you see that if the tube is flying straight into the wind, there is no lift force acting on the tube. But as soon as you tilt it and present a side of the tube to the wind, there is a force that is generated by the tube.

How big is this force created by the tube? It depends on the angle-of-attack. For angles less than 10 degrees, the force is very small and can be neglected. And that is what the Barrowman Equations do. They just assume the forces are so small that they are zero.

But for the sake of discussion, lets say that the force was not negligible. What would that do to our rocket? That is a great question.

To answer that question, we must first determine where the force on the tube acts. In other words, if the tiny forces acting on the entire length of the tube were summed up and concentrated to a single force (to make things simple), where would that force be concentrated at? That is pretty simple. Since the tube has a constant cross section and is therefore uniform from the top to the bottom, we could say that all the forces could be simplified to be concentrated right in the middle of the tube's length. Again see Figure 1.

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Why Do Tall Rockets Go Unstable?

Now that we know where the forces occur, we can add them to the other forces created on the rocket from such components as the nose cone and the fins. The goal here is to find out what would happen to the overall location of CP on the rocket. The question is, will it move backward, and make the rocket more stable, or will it move it forward and make it less stable?

In Figure 2, we see that since the middle of tube is ahead of the current CP, any new forces created by the tube at this middle point will move the CP forward on the rocket. The greater the forces, the more it will shift the overall CP of the rocket forward.

Once we realize this piece of bad news, we can start looking to what might happen for those really long rockets.

As Figure 3 shows, the CP will continue to move forward with an increase in the length of the body tube. It is possible that the CP could slip forward of the CG, thereby making the rocket unstable.

So to do a quick review here, on a normal rocket, the assumption that the tube contributes no forces is OK. But on a long rocket, the immense size of the tube may mean that the forces start to build to the point where you can't ignore them anymore. It is going to shift the CP forward, and

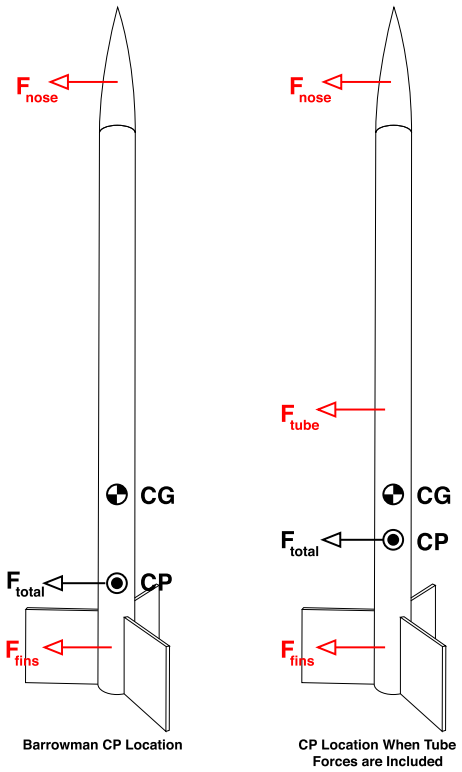

Figure 2: The forces created by the tube on the rocket will move the overall CP forward, making the rocket less stable.

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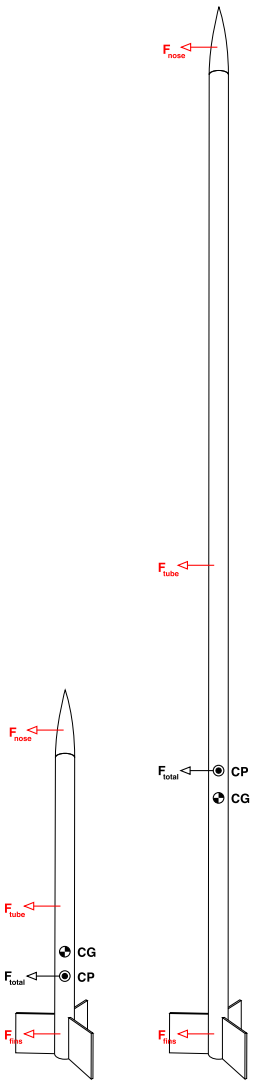

Figure 3: The longer the rocket, the further forward the CP is going to move. It could actually move ahead of the CG, making the rocket unstable.

could put the rocket on the hairy edge of instability.

The bad news is that neither the Barrowman equations nor RockSim, take this into account. The rocket will appear very over-stable. In fact, it will be so over-stable that modelers will worry about weather-cocking. This will then lead them to believe that they should make the fins smaller, as show in the middle rocket in Figure 4.

Because the equations don't take into account the tube forces on the rocket, the modeler should not make the fins smaller on the long rocket, but actually make them larger! This is counterintuitive, but it is what happens when the body contribution is taken into account.

If you've ever witnessed a superroc competition, which is a NAR contest event whose objective is to make an incredibly long rocket fly high or stay in the air the longest, you've probably noticed that a high number of the rockets do go unstable. Watching a long rocket perform a powered loop in the sky is pretty neat. The basic cause, as we've just

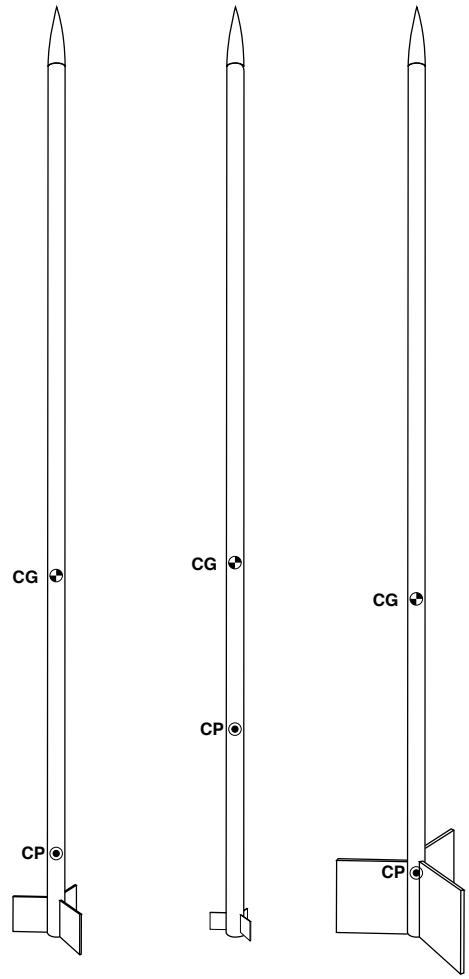

Figure 4: Left rocket shows the typical location of the CP from the Barrowman Equations. Middle: The modeler makes the fins smaller to try to reduce weathercocking. But this will actually make the model unstable. Right: The modeler should actually make the fins larger to increase stability.

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Why Do Tall Rockets Go Unstable?

discussed, is that the fins are too small to take into account the extra forces on the rocket generated by the tube.

And because the tubes are someone flexible, they usually will also kink in the middle because they can't maintain structural rigidity.

The flexibility of tubes is another problem association with long rockets. They are more like long wet noodles than a long stiff pole. Think about that for a second.

What is easier to do, to push a wet noodle, or to pull one? In fact, it is near impossible to push a wet noodle in a straight line. Give it a try sometime.

The exact same thing is happening with the long rocket. The engine is trying to push this long flexible tube in a straight line. The rocket is going to wobble on its way up. And this makes the movement of the CP even worse. Why?

Remember we said that the forces on the tube are pretty small at low angles of attack. But if the tube flexes, portions of it are going to be a really high angles of attack. So the forces skyrocket (do you like that pun?). It doesn't take long for the CP to shift ahead of the CG, and for the entire rocket to go unstable.

If you make a long rocket, you must put a lot of attention into making sure the tube doesn't have any curvature to it, and that it is extremely stiff so that it can resist bending. Otherwise, it ain't going to matter how big the fins are; the rocket will go unstable.

Instead of pushing a long rocket into the air with the motor at the rear, it might be better to use a tractor configuration where the motors are positioned at the front and the rocket is pulled into the air. This is what bottle rockets do. Figure 5 shows two tractor arrangements that might work well for those long rockets.

Even with the tractor arrangement, you still have to make sure the tube is rigid, or the fins could be at a different angle-of-attack than the front end of the rocket.

In the RS-PRO software, we took a different approach. Because the CP shift is important, we have the software shows the range of CP positions. On the 2D side view (Figure 6), it shows the CP at 0° Angle-of-Attack in a solid CP icon. Then it shows, in dotted line form, the CP at 90° Angle-of-Attach (the cardboard cut-out CP position). It then connects the two symbols with dashed lines to show you that the CP will move throughout the entire flight.

The center-of-gravity of the rocket also changes throughout the flight as the motor burns off propellant. The CG

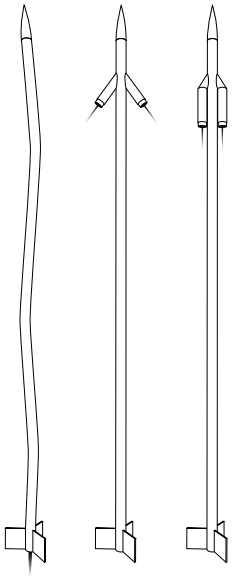

Figure 5: A motor in the back will cause some flexibility in the rocket, making it unstable. A better arrangement is to use a tractor configuration (two right images), to pull the rocket into the air.

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Elevate Eleven

EMRR's "Elevate Eleven" contest was to celebrate EMRR's Eleventh year and The Apollo 11's 40th Anniversary of landing on the moon. Contestants were to come up with something that promotes Eleven. Buy Eleven of the same rocket and launch them all at once. Make a rocket that looks like an Eleven. Take 11 kids out for a day of flying. EMRR didn't care, but expected to be impressed.

Hans "Chris" Michielssen asks himself, "How many Elevens could I possibly incorporate into a model rocket? "

There are 33 - "Elevate 11 Features". Here are some of them:

*** 11 sided parachute, 11 inches in diameter, 11 X 11" shroud lines**
*** Both body tubes are 11 inches long**
*** 11 fins that are 11 different sizes**
*** Fins made from 11 ply cardstock and paper overlays,**
*** 11 inches of Kevlar tied to,**
*** 44 inches of shock cord (four pieces of 11 inch elastic tied together.**
*** Launch with C11-5 Estes engine.**
*** Launched on May 2, 2009 at 11:11:11 a.m.**
*** Count down from eleven,**
*** Launch button pressed by an eleven year old girl named Emily.**
*** All rocket features - 33 in all - are divisible by 11!**

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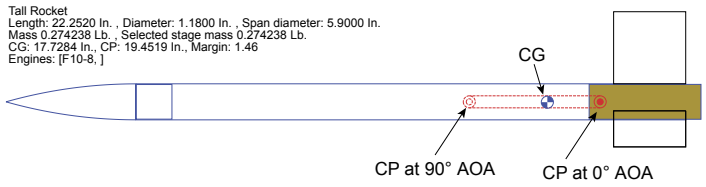

Figure 6: The 2D side view from the RS-PRO software shows the worst case CP position.

typically moves forward on the rocket, making the rocket more stable. This is a good thing.

If the CP and the CG are both moving forward, that offers us a little cushion in our stability margin once the rocket takes off. To show this, there is a stability chart in RS-PRO that shows that cushion because the CG is moving forward (see Figure 7).

From Figure 7 you can estimate the cushion in the static margin of the rocket by drawing a vertical line from the launch line to the burnout line. For example, at 0° angle-of-attack, the static margin of this particular rocket will increase from 1.5 to 2.8 as the propellant is consumed. Just as a reminder, the Static Margin is the distance between the CP and the CG divided by the diameter of the rocket. So it is a dimensionless number. Another way of thinking about it is that it is the number of tube diameters between the CG and the CP. The larger the number, the more stable the rocket is.

As long as the rocket doesn't fly at an angle-of-attack,

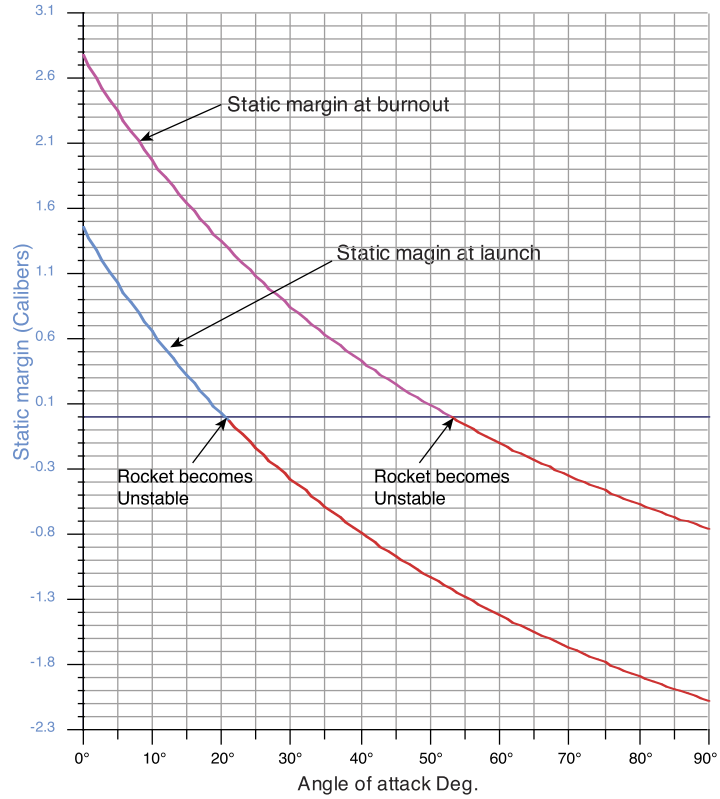

Figure 7: The difference between the static margin at lift-off and burnout is that the CG moves forward as the propellant is burned off.

everything will stay fine and the rocket gets more stable as it goes up.

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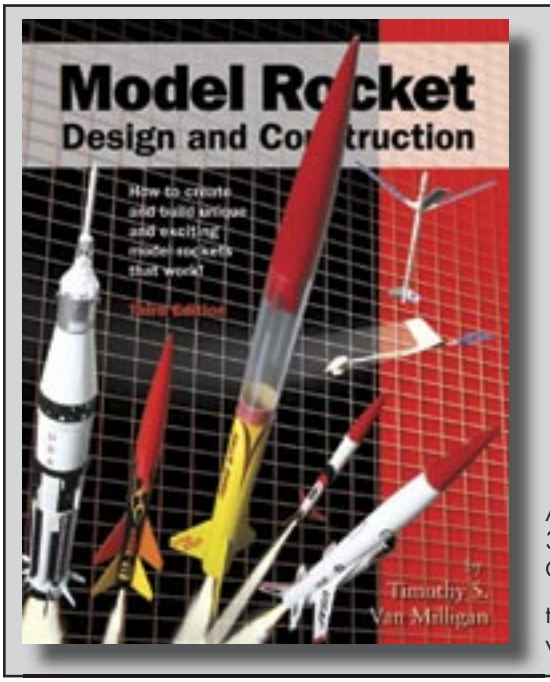

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But from Figure 7, if the rocket is launched straight up and immediately gets hit by a gust of a crosswind as it clears the launch rod, the CP shifts way far forward. In this particular design, the static margin becomes zero at around 20° angle-of-attack. The rocket is going to go unstable.

The good news is that if the rocket has already consumed its propellant by that point, the CG has shifted far enough forward that the rocket will still be stable. At a 20° angle-of-attack, the static margin is still 1.3 (top line) if the rocket has burned out.

Conclusion

Because the Barrowman equations ignore the forces on the tube, long rockets are a challenge to design correctly so that they remain stable throughout the entire flight. As a general design rule, if your rocket gets to be pretty long, don't make the fins smaller than the original fin-set that RockSim creates. If you have RockSim, you know it works. RockSim creates a generic set of fins to be used as a starting point whenever you add fins to a design. Don't make them smaller if you intend to make the tube longer later during the design process. That will keep you out of trouble.

And try to use a tube material that is stiffer than a paper tube. That will keep the rocket from bending and creating more aerodynamic forces on the model.

About The Author:

Tim Van Milligan (a.k.a. "Mr. Rocket") is a real rocket scientist who likes helping out other rocketeers. 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 the curator of the rocketry education web site: http://www.apogeerockets.com/education/. He is also the author of the books: *"Model Rocket Design and Construction," "69 Simple Science Fair Projects with Model Rockets: Aeronautics"* and publisher of a FREE e-zine newsletter about model rockets. You can subscribe to the e-zine at the Apogee Components web site or by sending an e-mail to: ezine@apogeerockets.com with "SUBSCRIBE" as the subject line of the message.