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APOGEE PEAK OF FLIGHT NEWSLETTER

Basics of Dynamic Flight Analysis
Moment of Inertia
Part 1

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Basics of Dynamic Flight Analysis

- Moment-of-Inertia (Part 1)

By Tim Van Milligan

Dynamic Stability is rarely discussed in rocketry circles; at least not compared to Static Stability. I suppose the reason is that it is tremendously complicated. Even I find the math pretty complex and daunting.

My goal in this article isn't to give you everything there is to know about dynamic stability. For that, you can pour through the book "*Advanced Topics In Model Rocketry*" by Mandell, Caporaso, and Bengen. You can find the book in the Apogee Components web store at: http://www.ApogeeRockets.com/topics_advanced_model_rocketry.asp.

What I want to give you is some of the key concepts and keep things simple so that you will know what to look for when your making your designs using the RockSim software. If it isn't usable information, then what good is it?

The Goal Of Dynamic Stability

The goal when designing a rocket, from the standpoint of "dynamics," is to create a rocket that has some favorable characteristics: 1) a rocket that is not easily deflected from intended direction of flight, and 2) the rocket quickly returns to a straight and true flight path once the disturbance has passed, as close to the original flight path as possible.

What makes designing rockets difficult from a dynamic standpoint is that there are many variables that have to be considered. In the case of *static* stability, you only have to look at just one: the stability margin. As long as the stability margin (the distance that the CG is forward the CP position divided by the maximum diameter of the rocket) is greater than 1.0, the model is assumed to be safe and ready to fly.

When studying the dynamic characteristics of a rocket, we have to look at many variables. And when you optimize one variable, another one gets worse. So there isn't a single number like in *static stability* that you can look at and say "if this number is greater than 1.0, the model is dynamically optimized." What you end up with is a trade-off. You get a rocket that is only optimized for a very narrow set of conditions. For example, the rocket may be optimized for achieving the highest possible flight, but it may not be able to withstand even a small wind trying to deflect its path.

So let's look at some of the variables and how the might affect the dynamic characteristics of our rockets. Besides looking at the variables, we'll use RockSim to view the effect of changing these variables.

We'll start with Longitudinal Moment of Inertia.

What is the Longitudinal Moment-of-Inertia?

Inertia is the property of an object to remain at constant velocity unless acted upon by an outside force. This is Newton's 1st Law of Motion.

Once you understand Inertia, the next step is to understand the "Moment of Inertia." It is defined as the inertia of a rigid rotating body with respect to its rotation. In simplistic terms, it relates the force required to make the object rotate*.

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*In the case of a model rocket, we assume that the rocket is rigid and can't bend. So we want to know how much force it is going to take to make the rocket rotate around the CG.

It doesn't take much of a force to rotate a rocket with a small Moment of Inertia value. On the other hand, a rocket with a large Moment of Inertia will require a bigger push (force) to get it to start rotating.

Pretty simple so far?

Since a rocket has three rotational axes: pitch, yaw, and roll (see Defining Moment article in Peak-of-Flight Newsletter 186 at http://www.apogeerockets.com/education/downloads/newsletter186.pfd), we have to specify which axis we are going to talk about. In this discussion, we're going to specify the pitch and yaw axes because the rocket is typically symmetrical around this axis. This is the LONG axis of the rocket, so it is called the longitudinal axis.

Then the Longitudinal Moment of Inertia relates the forces required to make the rocket rotate around the pitch and yaw axes of the rocket.

You're now past the hardest point of this discussion: the terminology. It gets easier and more fun from this point, I promise.

To summarize, the Longitudinal Moment of Inertia is proportional to the mass of the rocket, and where on the rocket that mass is located. A rocket that is heavier at the front or back has a higher Longitudinal Moment of Inertia than a rocket where the weight is concentrated in the middle. The higher the Longitudinal Moment of Inertia, the harder it is to get it to start rotating around the CG of the rocket.

Since the Moment of Inertia is tied to the mass of the rocket, it stands to reason that the model's Moment of Inertia is going to change throughout the flight of the rocket. Why? As the rocket engine burns, it expels mass out the rear. The rocket gets lighter, so the moment of inertia must decrease.

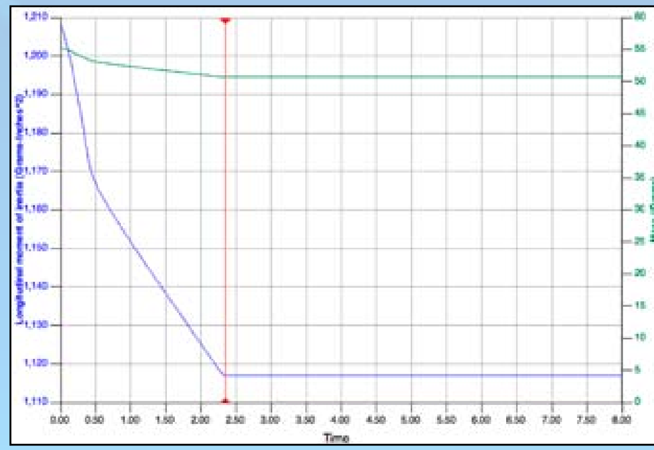

Figure 1

Figure 1: At the rocket burns propellant, the Longitudinal Moment of Inertia decreases because the mass decreases. Once it is done, the Longitudinal Moment of Inertia remains at a constant value for the duration of the flight.

Figure 1 shows a graph of Moment of Inertia of an Estes Alpha rocket during the burn of a C4-7 rocket engine. As the rocket gets lighter, the moment of inertia decreases. If you have RockSim, your first assignment is to display this graph of Longitudinal Moment of Inertia in mass versus time.

Changing A Rocket's Moment of Inertia

What does a rocket with a small Moment of Inertia look like? And what do you have to do to turn it into a large Moment of Inertia?

Remember, in *general terms*, a rocket that has a small moment of inertia is going to be lightweight and have a very short length. Most of the mass of the rocket is going to be positioned near the CG of the design. An Estes "Alpha" kit is a good example.

To make a rocket with a higher longitudinal moment of inertia, simply make it longer, and/or heavier.

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Figure 2 compares a typical Apha rocket, which has a small Longitudinal Moment of Inertia, versus a stretched version that has a higher value. The weight of the rockets is identical (the amount of nose weight in the rocket was reduced for the stretched version).

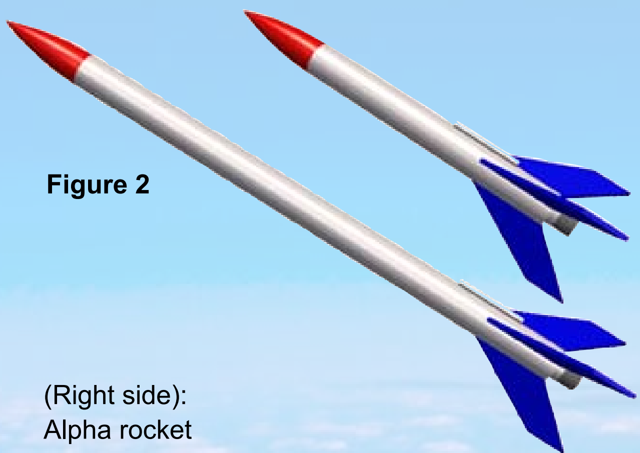

Figure 2

(Right side):
Alpha rocket
Empty Mass: 38.2 g
Longitudinal Moment of Inertia: 1116.9 g/in^2

(Left side):
Stretched Alpha rocket
Empty Mass: 38.2 g
Longitudinal Moment of Inertia: 3273.07 g/in^2

The important thing other than the length is where the mass is located in relation to the CG. For example, the nose cone is further away from the CG in the stretched version. It is this *distribution of mass* that affects the longitudinal Moment of Inertia of the rocket.

When designing rockets in RockSim, don't worry about the actual value of the Longitudinal Moment of Inertia number; every rocket will be different and there is no perfect value you should shoot for. Just note that one is larger than the other.

As we said above, a rocket with a higher Longitudinal Moment of Inertia is going to be harder to disturb from its initial flight path. We can show this by looking at some of the simulation graphs in RockSim.

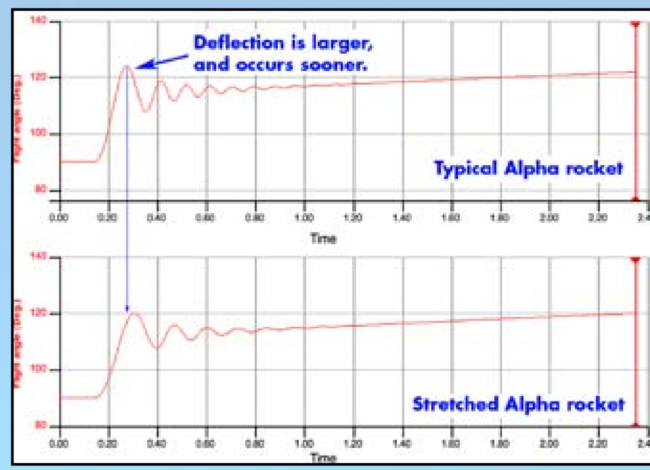

Figure 3

In **Figure 3**, what I did was to run two identical simulations of the typical Alpha versus the stretched Alpha. To keep them both the exact same weight, I reduced the nose mass in the Stretched Alpha slightly. In both cases the rocket was aimed straight up on a 36 inch launch rod, in a constant 20 mph wind using the Apogee C4-7 rocket motor. The graph show that at Time=0 seconds, both rockets were pointed straight up (90° from horizontal). At about 0.17 seconds, the rockets cleared the launch rod. Up to this point, both graphs are identical. That makes sense, because both rockets weigh the same, and should take the same amount of time to climb up the launch rod.

Once the rockets clear the launch rod, they now feel the affects of the 20mph wind. The shorter rocket reacts quicker, and turns toward the direction of the wind. The maximum deflection angle is about 123° measured from the horizontal.

Compare this to the Stretched Alpha rocket with its higher value of Longitudinal Moment of Inertia. It also turns toward the direction of the wind, but it does so at a slower rate. Also, the maximum deflection after it clears the launch rod is a lower value: 120° instead of 123°.

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This is good, right?

Yes. It is good from the standpoint that if your rocket gets hit by a brief and sudden gust of wind, the rocket with the larger Longitudinal Moment of Inertia is not going to react as quickly and will stay closer to its original course. In other words, it is going to stay closer to vertical.

BUT… *You knew there was going to be a downside didn't you, because at the beginning of this article I said there are always trade-offs in rocket design.*

The question we need to answer is: "Can your rocket have Longitudinal Moment of Inertia that is too great?"

The answer is yes. Too great of a value for the Longitudinal Moment of Inertia can make your rocket fly LOWER in breezy conditions.

In this particular simulation, comparing the typical Alpha to the Stretched Alpha, the typical Alpha flies higher!

"HUH" you ask?

Didn't we just say that the Stretched Alpha went straighter coming off the launch pad? Yep, that's right. The Stretched Alpha has a straighter flight path. The table below compares the altitude and range values of the flights. Remember, everything (mass, motor used, size and shape of the fins) is the same except the Longitudinal Moment of Inertia: **Table 1**

Rocket	Max Velocity (mph)	Apogee (ft)	Distance at Apogee (ft)
Typical Alpha	236.6	1266.47	700
Stretched Alpha	224.7	1182.07	540

As you can see in the table, the stretched Alpha was indeed straighter because its distance at the apogee point has a lower value. But notice that it didn't go as high, nor as fast as the typical Alpha rocket kit.

If the Stretched Alpha is flying *straighter*, why doesn't it go higher?

The answer is "drag."

The drag force varies with angle-of-attack. The higher the angle of attack, the higher the drag. Makes sense doesn't it?

But wait... didn't we say that the Stretched Alpha didn't reach as high of a flight angle coming off the launch rod? It was only about 120° versus 123° for the typical Alpha rocket kit (review Figure 3 again). You are VERY smart to catch that.

The Stretched Alpha didn't have as high an angle of attack, but when it was at an angle-of-attack, it stayed there for a longer period of time. The shorter Alpha reacted quicker and zeroed out its angle of attack faster. So the cumulative effect is that the Stretched Alpha was creating more drag throughout the entire flight than the typical Alpha kit -- because it lingered longer when it was at an angle-of-attack. So the typical Alpha kit flew higher.

Remember we also said that while a larger Longitudinal Moment of Inertia won't deflect as far, it is going to take LONGER to get to that peak point.

We can see this in Figure 4. (page 6) You can see at any time point, the stretched Alpha is going to be at a higher angle-of-attack. This means a higher drag force that retards the forward progress of the rocket.

Figure 4: (page 6) The stretched Alpha is flying at a higher angle-of-attack, so it has a higher amount of drag.

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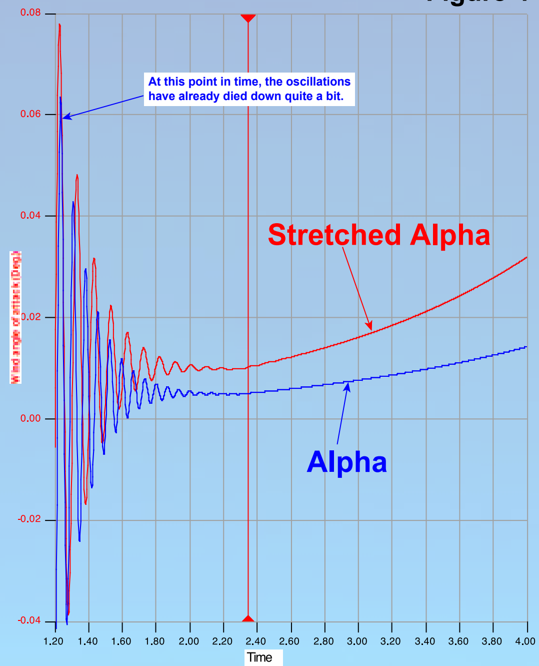
Figure 4



It does get complicated, doesn't it?

I'll restate the goals of designing a rocket from the standpoint of "dynamics." As you read earlier, we desire the following favorable characteristics: 1) The rocket is not easily deflected from intended direction of flight, and 2) the rocket quickly returns to a straight and true flight path once the disturbance has passed and so it is as close to the original flight path as possible.

To sum up our Stretched Alpha experiment: by increasing the Longitudinal Moment of Inertia, we satisfied the first characteristic. But we failed at the second because it took too long to return to the desired flight path. "Time" is what we didn't optimize.

This leads us to one final question we need to ask: "was it good or bad to stretch the Alpha rocket?"

Answer: it depends on your mission objective for the rocket. If you wanted the straightest trajectory, then making it longer was a good idea. But if you wanted the highest flight, then it was bad.

Conclusion

The purpose of this exercise was to show the affects that changing a rocket's Longitudinal Moment of Inertia has on the trajectory of a rocket. It is just one of the factors that you control when you design a model.

If you don't have RockSim, you're missing a lot of key information that you need to optimize your rocket's design. I recommend that you check it out today by downloading the free 30-day trial version today at: http://www.ApogeeRockets.com/rocksim.asp. There is really no way to truly optimize a rocket for its intended mission without it.

In future articles, I hope to go over some of the other variables that control the dynamic characteristics of a rocket. But in the mean time, play around with RockSim and see how fascinating it is to change the configuration, and how those changes affects the trajectory of the rocket. Don't be afraid to make changes; you aren't going to break anything. The more you play with RockSim the more you'll learn about rocketry.

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.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Foam board fins for a different build. Includes pre-printed side panels. Plastic nose cone. 19" long 0.976 dia.
Space Speedster
Printed body with foam board fins. Preprinted fins. Laser cut foam mounting rings.
Flechette
3 fins 6 piece laser cut balsa. Flights to 1000'/ 300m. Parachute recovery.
Flechette: The word flechette is French for "dart." In military use, it is a projectile having the form of a small metal dart: a sharp-pointed tip and a tail with several vanes to stabilize it during flight.
Explorer
Laser cut 4 fin with distinctive design. 21" long 0.976" dia Parachute recovery. Flights to 750'/ 250m
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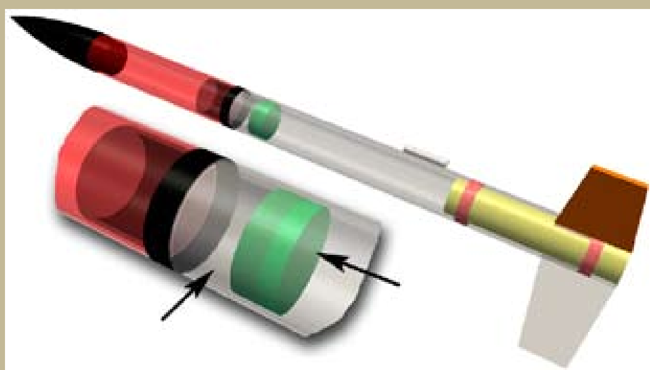
Question & Answer

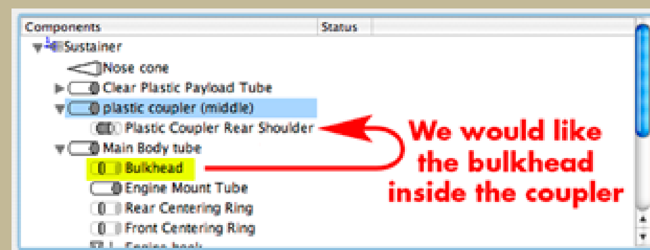
Q: How do I put a bulkhead inside a tube coupler in RockSim?



A: The design-rules within RockSim do not allow the bulkhead component to be attached to the coupler component in the parts tree.

First, attach the bulkhead to a body tube in the parts tree.

Then edit the location of the bulkhead. Sometimes the location may be a positive number, sometimes it may be negative.



Also, turn off the "Autosize" feature of the bulkhead, and physically type in the outside diameter dimension of the bulkhead so that it matches the inside diameter of the tube coupler. If you leave Autosize on, the outer diameter will be too big to fit inside the smaller coupler tube.

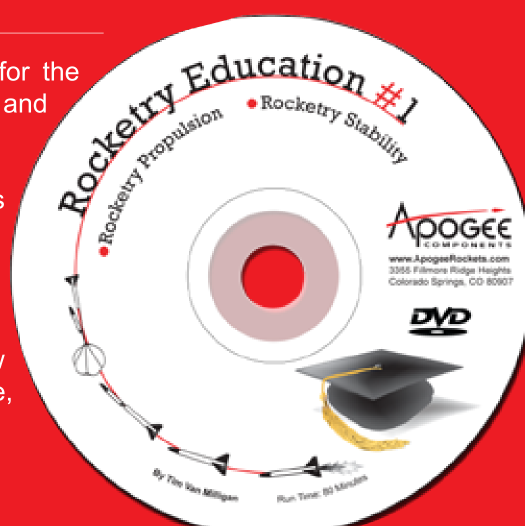
The design rules of RockSim prevented us from putting the components in the desired locations in the parts tree. But with a little imagination and ingenuity, we were able to force them in the proper place. Don't be afraid to try this with other parts, like putting fins on nose cones. It works great!

New Rocketry Education DVD

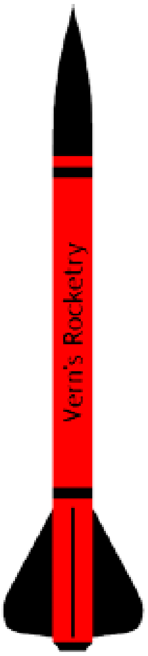
This DVD was videotaped at a graduate course I presented for the Space Foundation as part of their summer institute course “Rocketry and the Biology of Living in Space, Space History, and Space Law.”

The purpose of my particular presentation was to give teachers a strong foundation in rocketry, so that they could be ready to take it back to their classrooms. There was particular emphasis on rocket propulsion and rocketry stability. In the rocket propulsion discussion, we talked about the physics - how rockets produce thrust, the types of propellants used in model rocketry, characteristics of high and low thrust motors, the nomenclature for rocket motors, the thrust curve, and how to select the best motor for a model rocket.

Find it at http://www.ApogeeRockets.com/Teacher_DVD.asp



Web Site Worth Visiting



http://www.vernk.com/index.htm

Vern Knowles has a nifty web site that is definitely worth visiting. Vern likes his rockets big, and if you are thinking about getting into large rockets yourself some day, then you'll find all sorts of useful information on this site.

For starters, he has a number of different calculators to figure out things like: amount of ejection charge needed based on rocket volume, and altimeter port-hole sizes. He then has a lot of useful information like a comparison of different altimeters versus GPS data, and the ignition current requirements of different types of electric matches.

There is a lot of useful information on this site, particularly for high-power enthusiasts. For example, I love the way he describes his projects with step-by-step pictures. One that caught my eye was how to hook up redundant ejection charges in a big rocket.

His links section is a must-see too. He has a ton of them sorted by different topics, from manufacturers to construction supplies. And none of it looks cluttered, so you'll find it is an easy navigate web site.

TIP OF THE FIN

I had a pointy nose cone made out of balsa wood. Just before I was about to paint it, the nose fell out of the tube and smashed off the tip portion on the concrete floor. Yep, that bone-head stuff happens to me too.

How am I going to fix it, you ask? We're going to use Fix-It Epoxy clay (http://www.ApogeeRockets.com/epoxy-clay.asp).

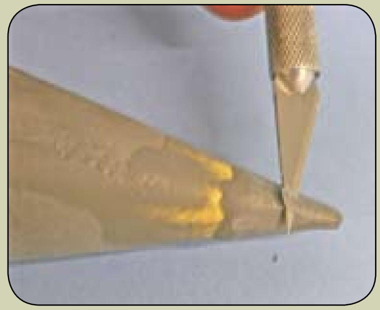
1. Take a short piece of wire (a 1 inch long piece of paperclip will work just fine), and press it into the tip of the nose. Make sure it is straight. It should stick out slightly shorter than the actual length of the nose prior to being damaged.

2. Take a sharp hobby knife and scuff up the end of the damaged nose. We want lots of surface area for the epoxy clay to grab an hold on to.

3. Now, using water-thin CA, soak the fibers of the exposed balsa wood. This will also glue the metal wire into the nose cone. Wipe off the excess CA before it hardens.

4. Mix up a small glob of Fix-It Epoxy clay, and stick it onto the tip of the nose cone. Try to press it tightly into the nooks and crannies of the balsa wood. The metal wire is also going to give the epoxy-clay something to grab on to.

5. Carefully watch the epoxy clay. In about an hour, it will start to stiffen up. At this point, you can take your



hobby knife and start to shape it using a carving action. This is tricky to catch at the right time; it has to be stiff enough to carve, but not too hard or you could accidentally pull the whole glob off the tip. You don't have to be perfect. The idea is to remove enough of the epoxy so you don't have to spend too much time sanding.

6. When the epoxy is totally hard (I'd wait overnight for it to harden), you can start sanding it down with some rough grit sandpaper. When you get the shape right, you can switch to finer and finer grits.

7. Use a sandable primer to fill any tiny voids prior to the final coat of paint.

When you are done, the nose cone will look brand new. And since it now has an armor plating of Fix-It epoxy, it will be much harder to damage the next time you drop it.