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PEAK OF FLIGHT

N E W S L E T T E R

BASICS OF DYNAMIC FLIGHT ANALYSIS

PART 5

The Damping Ratio

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Corner

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Basics of Dynamic Flight Analysis Part 5

The Damping Ratio

By Tim Van Milligan

This is the fifth part in the series of articles on Dynamic Flight Analysis. If you are just seeing this for the first time, the first four parts were covered in newsletter **192, 193, 195 and 196**.

What we've been doing in this series of articles is to look at the parameters of a rocket's design that determine how it behaves in flight. This is important because the dynamics control the trajectory of the rocket, and we want to know what the rocket will do once it leaves the pad. Not only do we want things to be safe, we can actually optimize our design to make the rocket perform better. In the last article, we gave the first optimization parameter that you can use to design rockets that fly higher.

I'm using the book *Topics in Advanced Model Rocketry* as my guide as I write these articles. I recommend it to anyone who wants to dig deeper into the study of dynamic stability. You can get your own copy from the Apogee Components web site at: http://www.ApogeeRockets.com/topics_advanced_model_rocketry.asp

As a quick review, there are five parameters of fundamental importance to a rocket's dynamic characteristics. They are:

I_L = Longitudinal Moment of Inertia
 C_1 = Corrective Moment Coefficient
 C_2 = Damping Moment Coefficient
 I_R = Radial Moment of Inertia
 ω_n = Natural Frequency

To make analysis of a rocket's design easier, a 6th

parameter is added as a convenience. It is called the "Damping Ratio." The formula for this parameter is:

$$\zeta = \frac{C_2}{2\sqrt{C_1 I_L}}$$

ζ = Damping Ratio

As you can see from the formula, there are no new terms that we haven't seen before. The Damping Ratio is computed after we have found the Longitudinal Moment of Inertia, Corrective Moment Coefficient, and the Damping Moment Coefficient.

Recall from **Newsletter 193** that the Corrective Mo-

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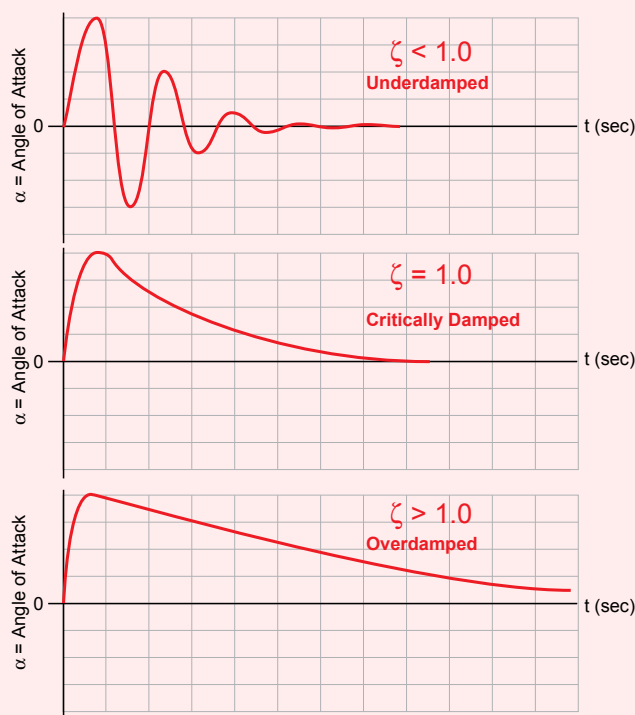


Figure 1: The damping ratio tells us how a rocket is going to respond to a disturbance in flight. For example, whether or not it will oscillate.

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ment Coefficient varies as the velocity *squared*, and that the Damping Moment Coefficient varies directly with velocity. But since we're taking the square-root of the Corrective Moment Coefficient in the denominator of the equation, the velocity units cancel out. Because of this, the Damping Ratio is a dimensionless number, and it is independent of the speed of the rocket! It will then be possible to do define "acceptable" and "optimum" values for a truly optimized rocket.

But before we get to optimized rockets, what does the Damping Ratio tell us? For that, we need to look at how a rocket might respond to a disturbance. Figure 1 shows three things that could happen.

If the Damping Ratio is less than 1.0, the rocket is going to oscillate back and forth. The smaller the Damping Ratio value, the faster the oscillations will be. In other words, the Natural Frequency is going to be higher (see [newsletter 196](#) for a discussion on Natural Frequency).

As the Damping Ratio approaches 1.0, the oscillations get fewer and fewer. When it is exactly 1.0, the rocket doesn't oscillate at all. It will come right back to zero degrees angle of attack. This is called *critically damped*.

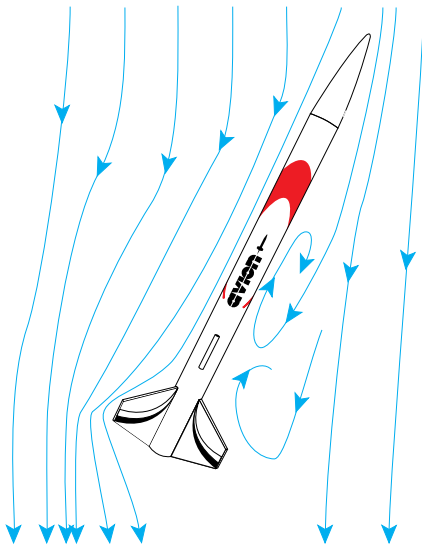


Figure 2: Drag will increase when the rocket flies at an angle-of-attack.



If the Damping Ratio is greater than 1.0, the rocket is said to be *overdamped*. In this case, the rocket never comes back to zero degrees angle-of-attack. It will always be flying at some positive angle, and thus the drag on the rocket will never be minimized. Remember that drag is always minimized when the angle-of-attack is zero degrees. When it is not zero degrees, the rocket presents its side to the airstream (like crab-walking sideways), which increases the frontal area of the rocket. See Figure 2.

What Damping Ratio is the best?

My first reaction is probably like yours. That the critically damped case would be the best. Who wants their rocket oscillating back and forth?

Actually, you do want it to oscillate back and forth. For one thing, you'll rarely encounter a quick disturbance. A quick disturbance would be something like a bird flying into your rocket from the side. It strikes the

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rocket once, and goes away. In real life, the disturbance is going to be continuous, like a steady wind from one direction. In that case, the rocket is always going to be turning one way and is really going to weathercock hard into the wind. By oscillating back and forth, it won't turn as far into the wind; meaning the weathercocking will be less and the rocket will be going straighter up.

The other reason you want the rocket to oscillate is so that the amount of time it spends at an angle-of-attack is minimized. As we said before, the drag increases when the rocket is flying at an angle-of-attack. So it won't go as high or as fast if the rocket is critically damped because it takes quite a long time for it to come back to zero degrees angle-of-attack.

At this point, we know that underdamped motion is most desirable for model rockets. But how much underdamping should we shoot for when designing rockets?

Figure 3 shows two similar rockets that fly into a layer of air with a strong crosswind. The major difference between the rockets is that one rocket has forward fins which increase the Damping Moment Coefficient (and hence the Damping Ratio). Notice in the chart that the higher Damping Ratio does not oscillate as fast, and the oscillations die down faster.

If you wanted to dampen out the oscillations as quickly as possible, the optimum Damping Ratio would

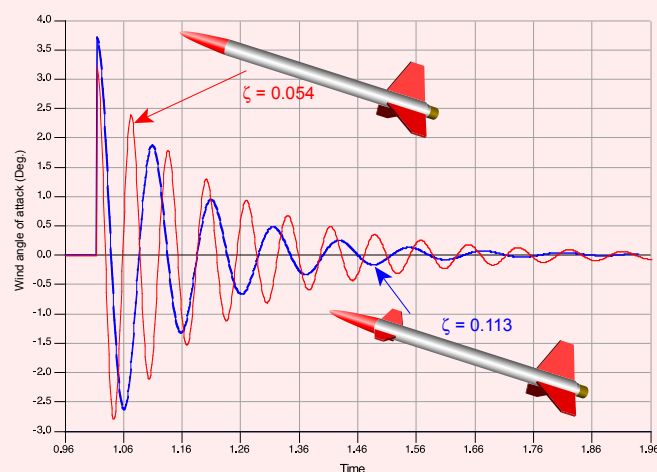


Figure 3: A rocket with a higher damping ratio will restore quicker to zero degrees angle of attack faster.

be equal to 0.7071 (See *Topics in Advanced Model Rocketry*, page 101). However, this is not the best Damping Ratio if you want your rocket to fly the highest possible in breezy conditions.

While the rockets with high Damping Ratios zero out the oscillations quicker, it turns out that they don't fly as high. The reason is that the extra fin area needed for higher Damping Ratios adds a lot of extra drag.

Do you see how designing rockets has a lot of tradeoffs? We can either dampen out quickly, or we can reduce the drag and fly a little bit higher.

Design Criterion: The book *Topics in Advanced Model Rocketry* (page 256) recommends a Damping Ratio between 0.05 and 0.30. The higher value is considered too light for good ballistic performance, so you really don't want to design a rocket with a Damping Ratio higher than that. For altitude-optimized rockets, you want to be closer to that lower limit. If you get a Damping Ratio below 0.05, there are some roll-coupled resonant issues that get pretty catastrophic. That is beyond the scope of this article, but you can get more information about it in the aforementioned book.

Using this Information with RockSim

Getting the Damping Ratio from RockSim is easy, but you have to run a simulation first. After running a simulation, simply go to the graph section and plot out the Damping Ratio. See Figure 4 on the next page.

As can be seen from Figure 4, the Damping Ratio is not static during the burn of the motor. Refer to the Damping Ratio equation that was listed previously. During the motor's burn, the rocket's Longitudinal Moment of Inertia is decreasing because the rocket is losing weight. So typically you'll see the Damping Ratio increasing during the powered portion of the flight (Figure 4, call-out "A"). In other words, if the denominator is decreasing, the value for the Damping Ratio will be increasing.

But it can also decrease during the burn phase of the flight if the jet damping is significant. The jet damping affects the Damping Moment Coefficient, which is

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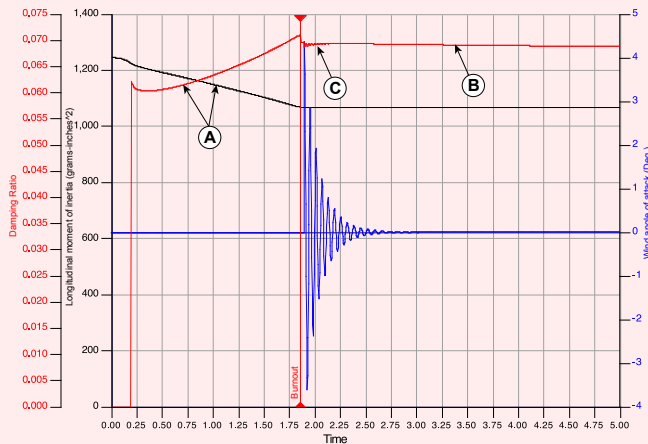


Figure 4: Plot out the Damping Ratio graph after running a simulation. This is a graph of an Estes Alpha rocket on a C6-5 motor.

the numerator of the equation. So if the Damping Moment Coefficient increases at a greater amount than the longitudinal moment of inertia is decreasing, the graph

may show the Damping Ratio increasing during the burn of the motor.

After the motor burns out, the Damping Ratio becomes fairly constant. You might notice that it does decrease slightly; this is because the air density decreases as the model ascends into the sky (Figure 4, call-out "B"). The density value is in both the numerator and the denominator of the Damping Ratio formula. But since we're taking the square root of it in the denominator, it affects the numerator much more. So if the air density decreases, as it should the higher up the rocket goes, then the numerator gets smaller and the Damping Ratio will decrease too.

It is during this linear portion that you will take your reading for the rocket's Damping Ratio. As mentioned previous, the value of the Damping Ratio during the coast phase should be between 0.05 and 0.3.

When running the simulation in RockSim that created the graph in Figure 4, I set the wind conditions so that at 450 feet up, the rocket is hit by a 20mph wind. That is why the wind-angle-of-attack goes crazy after engine burnout. During this period of oscillation, the Damping Ratio will also oscillate slightly as the rocket's Normal Force Coefficient changes when the angle-of-attack changes (Figure 4, call-out "C"). Like air density, the Normal Force Coefficient is in both the numerator and the denominator of the Damping Ratio equation, but they don't cancel out because the square root is taken in the denominator. It isn't important, I just wanted to explain why it happens in case you were wondering.

Increasing the Damping Ratio

If your rocket's Damping Ratio is too small, meaning it will oscillate wildly, you can increase it by increasing any of those parameters that will increase the Damping Moment Coefficient, or by decreasing the Corrective Moment Coefficient or Longitudinal Moment of Inertia. You can:

1. Add more fin area
2. Move the fins further away from the CG
3. Sweep aft fins rearward and canard fins forward

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4. Decrease the rocket's weight
5. Shorten the rocket's length
6. Move the heavy items closer to the middle of the rocket.

Decreasing the Damping Ratio

If your rocket's Damping Ratio is too large, you can decrease it by:

1. Reducing the fin area
2. Moving the fins closer to the CG
3. Sweeping aft fins forward and canard fins rearward
4. Increasing the rocket's weight
5. Lengthening the rocket

6. Moving the heavy items further to the front and rear of the rocket.

Now that we know a lot more about rocket design, let's test our knowledge. Figure 5 shows a number of improperly designed rockets that are not optimized for best altitude. There is an explanation for each one on what is wrong with the design.

Conclusion:

The Damping Ratio is a great number to look at, as it takes a lot of the trial and error out of designing high-performance rockets. Since it is a simple *number*,

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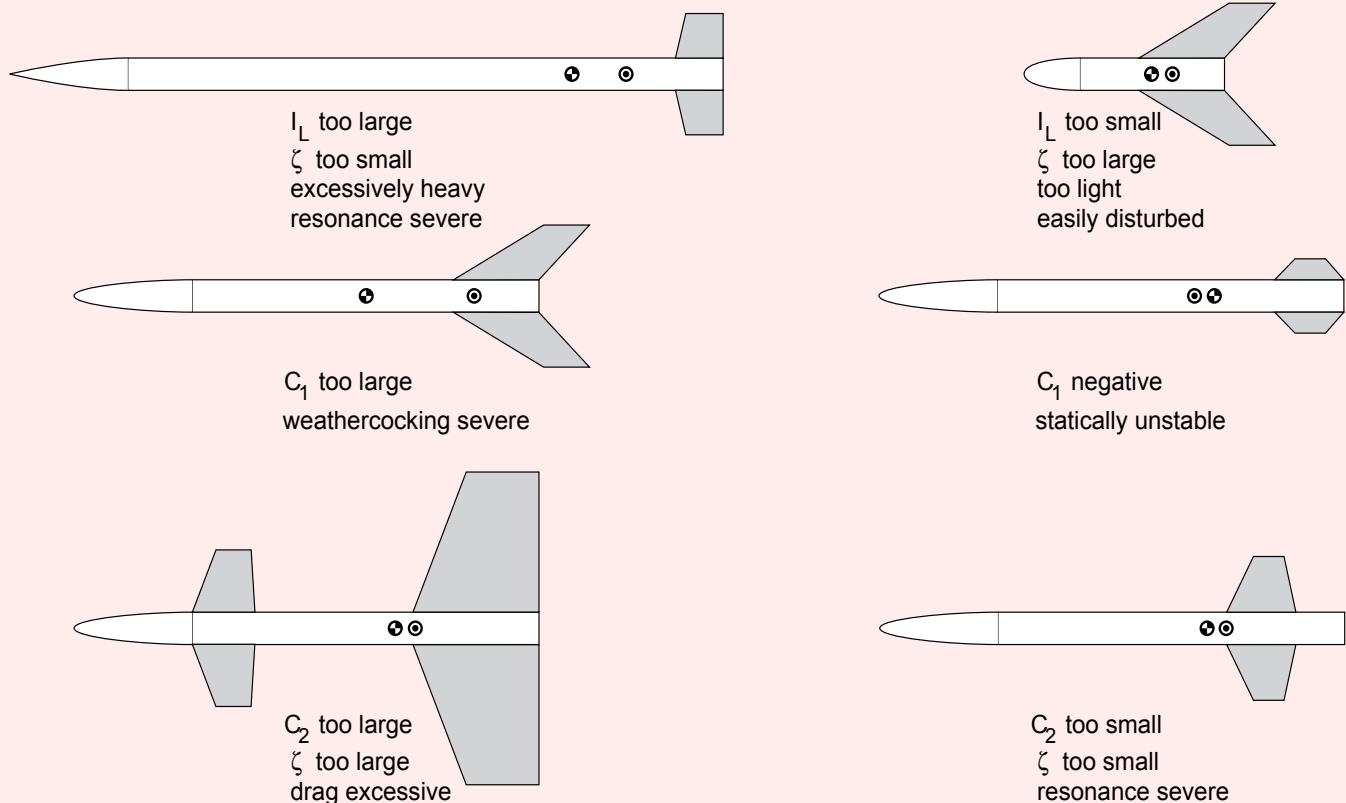


Figure 5: Rockets that need to be redesigned. Recall: I_L = Longitudinal Moment of Inertia, C_1 = Corrective Moment Coefficient, C_2 = Damping Moment Coefficient, ζ = Damping Ratio. Source: *Topics in Advanced in Model Rocketry*, page 244.

Continued from page 6

you can quickly look at the Damping Ratio and see if we need to increase it or decrease it to an acceptable value by changing the design of the rocket.

As designers, we all like simple number-type parameters. It is like a rocket's "optimum mass;" you're either right at the number, or you know what you have to do to get the rocket to be at that weight. The Damping Ratio is a lot like this, but we have a little bit of wiggle-room because we only have to be in the range of 0.05 to 0.30.

The key ingredient of course, is to use RockSim to design your rockets.

I'm sure that Gordon K. Mandell, who wrote the article in 1968 for *Model Rocketry* magazine called "Fundamentals of Dynamic Stability" would appreciate RockSim's dynamic treatment of a rocket's flight. That nearly 40 year-old article was the foundation of the chapters

he wrote for the book *Topics in Advanced Model Rocketry* that was published in 1971, and is where I got information for this series of articles. He'd probably say: "Finally... all that work I did writing about flight dynamics is presented through the RockSim software, which makes it easy to design optimized rockets. It's about time..."

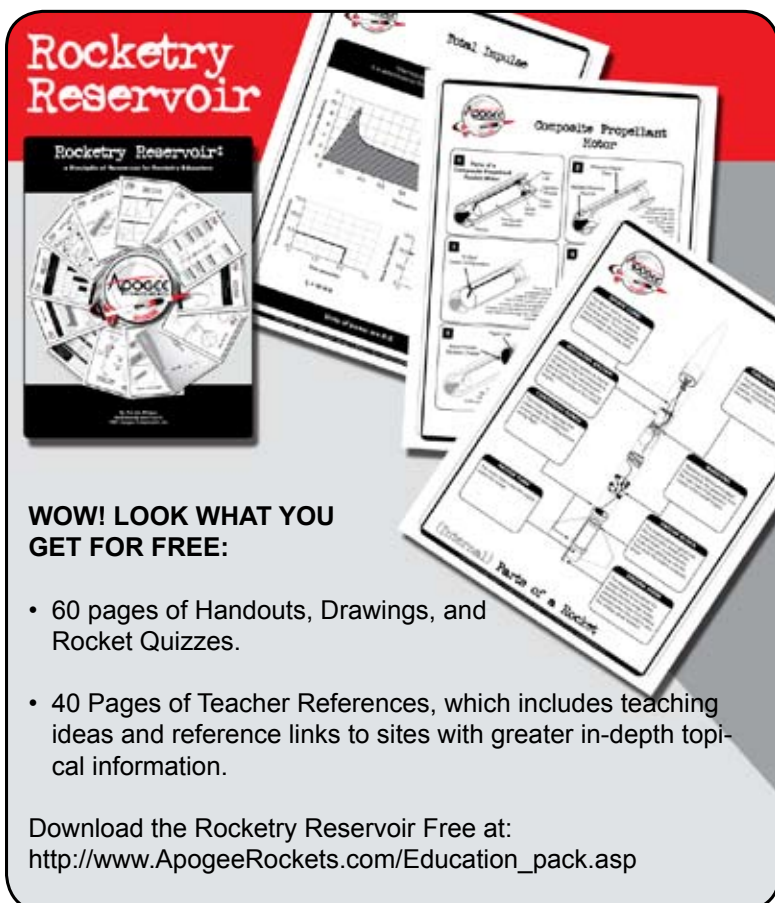
If you don't have it yet, you can get the RockSim software today at: <http://www.ApogeeRockets.com/rocksim.asp>

You should now have enough information to design dynamically optimized rockets. In the next article in this series, I'll walk you through the whole process of optimizing a rocket. I'll try to lay it out in a 1, 2, 3 process so that you'll have everything at your fingertips to create awesome models using the RockSim software.

If you enjoyed this article, or you've learned something new, I would appreciate it if you would send me a note. I'm interested in your opinions about our newsletter and how we can make it better.

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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Question & Answer Corner

Using Rockets to Perform Ballistic Studies

By Tim Van Milligan

I get questions all the time from teachers that want to use model rockets to perform the classic ballistic experiment. The idea they want to show students is that there is an optimum launch angle that will yield the longest flight of a rocket.

In a perfect world, where there is no drag acting on the projectile, the answer is that a 45° launch angle will give the furthest distance.

Well, rockets are fun, so why not use them for this experiment? My answer is "don't!" Rockets are fun, but the experiment is dangerous. In order to perform this experiment properly, you have to glue the nose cone on the rocket and tilt the launch rod at a serious angle. Both of these violate the NAR safety code.

There is a better way to perform this experiment, and do it in a safe way: use RockSim. You can get

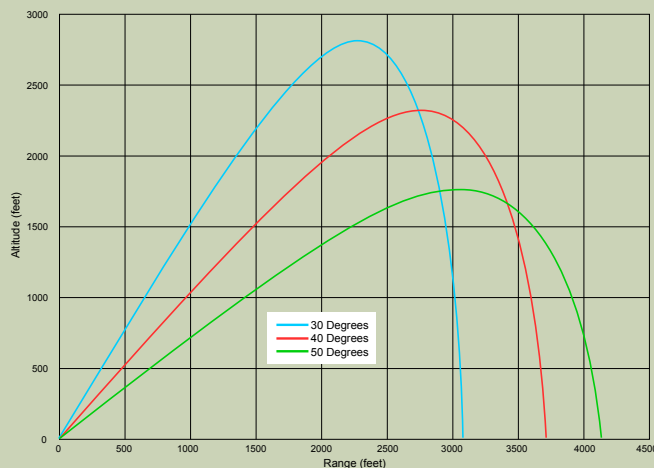


Figure 1: What is the optimum launch angle that yields the furthest trajectory? This is a good experiment for RockSim.

RockSim at: <http://www.Apogeerockets.com/rocksim.asp>

RockSim will allow you to perform launch simulations in a realistic fashion, but without the slight errors that can creep into the experiment, like a gust of wind or a thermal that might push the rocket a little off course.

Additionally, the student will also get to learn how to use a spreadsheet so that they can make graphs like the one shown here.

Not only can the students find the optimum launch angle, they can perform additional experiments like:

1. What is the optimum launch weight for the furthest distance?
2. Does the launch angle change with rocket weight?
3. Does the optimum launch angle change with different rocket engines? (high thrust vs low thrust)
4. Does changing the density of air change the optimum launch angle?
5. Does the optimum launch angle change if there is a head wind or a tail wind?

As you can see, there are many variables that you can change. If you were using real model rockets, the cost to do these experiments would be astronomical. That's one of the great benefits of RockSim; it saves you money.

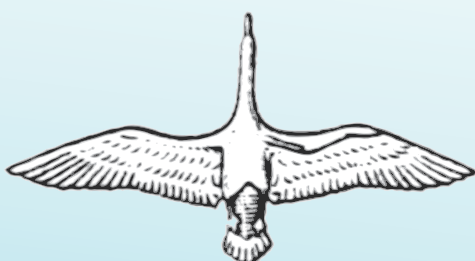
If you wanted to save a little extra time, be sure to use the SMARTSim software too. It allows you to run experiments like these to get optimum solutions in a very short amount of time. Check out SMARTSim at: <http://www.ApogeeRockets.com/smartsim.asp>

If you need some additional help on using a spreadsheet to make charts, check out our video tutorial on our web site at: http://www.apogeerockets.com/education/teaching_tips.asp

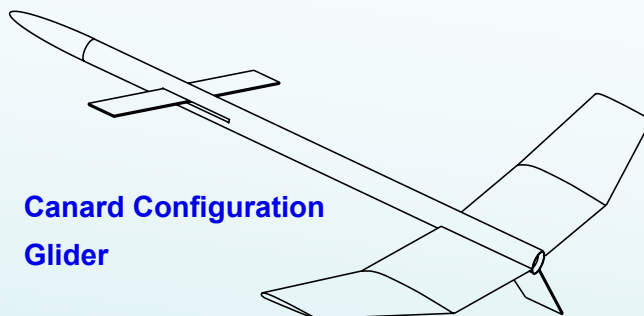
DEFINING MOMENTS

"Canard"

Canard is the French word for duck. What does this have to do with aviation and rocketry? The thing that makes the duck look different is its long neck, which makes the wings look like they are near the back end of the bird.



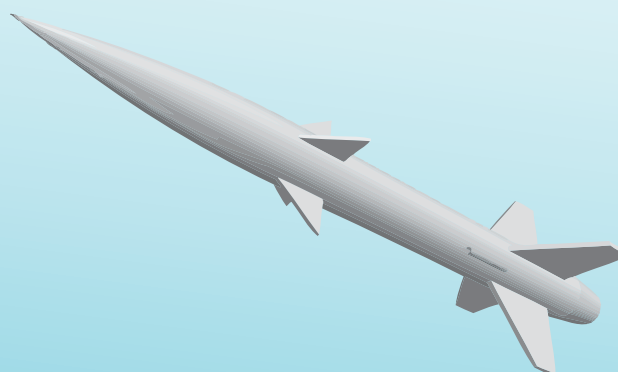
In aviation, if you have a vehicle that has wings at both the front and the back, and the back wings are much larger than the front wings, then we call this a



**Canard Configuration
Glider**

"canard configuration."

You can have a similar configuration with fins at both ends of the rocket. This is also known as a canard configuration vehicle.



On the rocket, the front fins are destabilizing. That means that if they are improperly sized, the rocket can be statically unstable. Care should always be exercised when using the canard configuration on rockets. Always test them in RockSim to be sure.

A way to reduce the destabilizing effect of the forward fins is to allow them to swivel freely. See *Peak-of-Flight Newsletter #150* (<http://www.ApogeeRockets.com/education/downloads/newsletter150.pdf>) for more details on this technique.

Duck drawing source: *Vertebrate Flight. Mechanics, Physiology, Morphology, Ecology and Evolution*. By U.M. Norberg. ©1990.

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