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Issue 647 / March 11th, 2025

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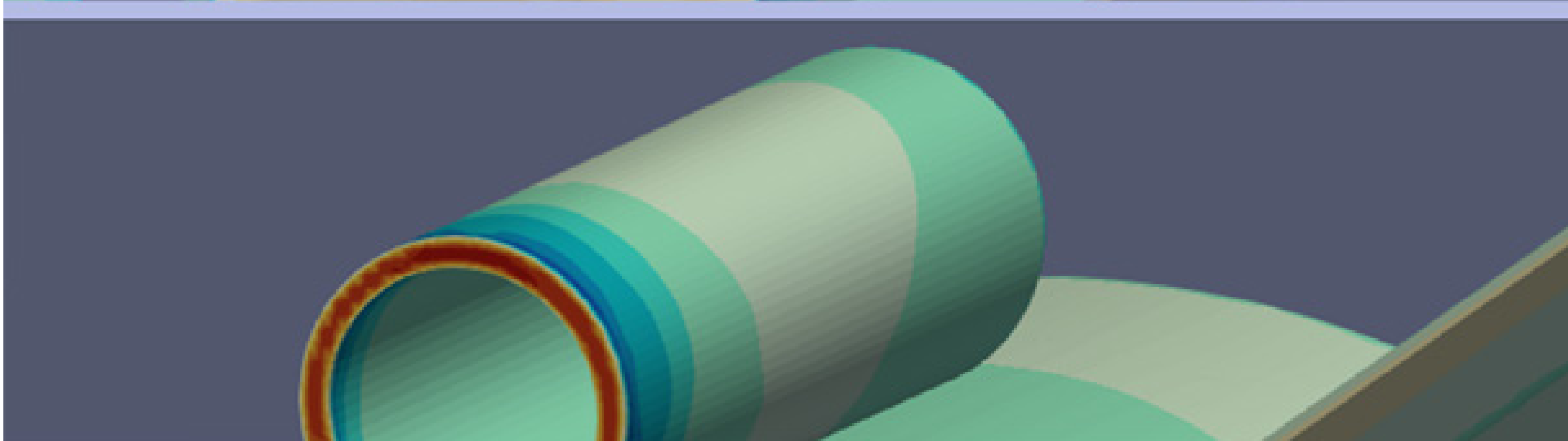
Computational Fluid Dynamics for Model Rocketry Pt. 4



PEAK OF FLIGHT NEWSLETTER

Issue 647/ March 11th, 2025

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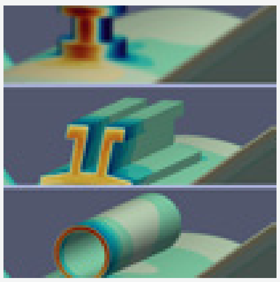

Computational Fluid Dynamics for Model Rocketry Part 4

FEATURED ARTICLES

Computational Fluid Dynamics for Model Rocketry Part 4

by Ken Karbon

Part 4 of CFD for Model Rocketry focuses on some examples of CFD Analysis that can be useful for model rocket design.

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PEAK OF FLIGHT NEWSLETTER
Computational Fluid Dynamics For Model Rocketry Part 4
Issue 647 / March 11th, 2025
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A Guide to Computational Fluid Dynamics for Model Rocketry Part 4

by Ken Karbon

Introduction

After covering CFD theory, methods, and software training in the previous newsletters, this article will illustrate some examples of CFD analysis useful to model rocket design. The main motivation for these studies is to overcome limitations in other simulation tools, namely Cd and CP prediction. While the CFD modeling is much more difficult and time consuming than software like RockSim, it is worth the effort in cases where accuracy and performance are critical. The wealth of visual and numerical data from CFD also help to understand the aerodynamic behavior at a deeper level.

Comparing Drag Coefficient of Launch Guides

Cd is a straightforward result from CFD simulations. Rocket CFD models can be of any shape and complexity, and the drag forces will be calculated along with the flow field around the vehicle. This is a huge advantage over the classic empirical drag models which are limited to basic shapes like nose cones, body tubes, and fins.

A common question is often, “What has the lower drag: launch lugs, rail buttons, or rail guides – and lower by how much?” There is some historical measurement data of launch lugs, but very little data is known about the other two types of appendages. This makes for a good CFD study.

PEAK OF FLIGHT NEWSLETTER

Issue 647 / March 11th, 2025

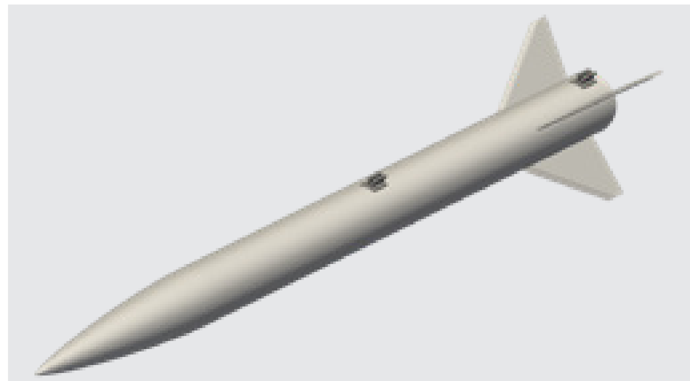
www.ApogeeRockets.com

Computational Fluid Dynamics For Model Rocketry Part 4

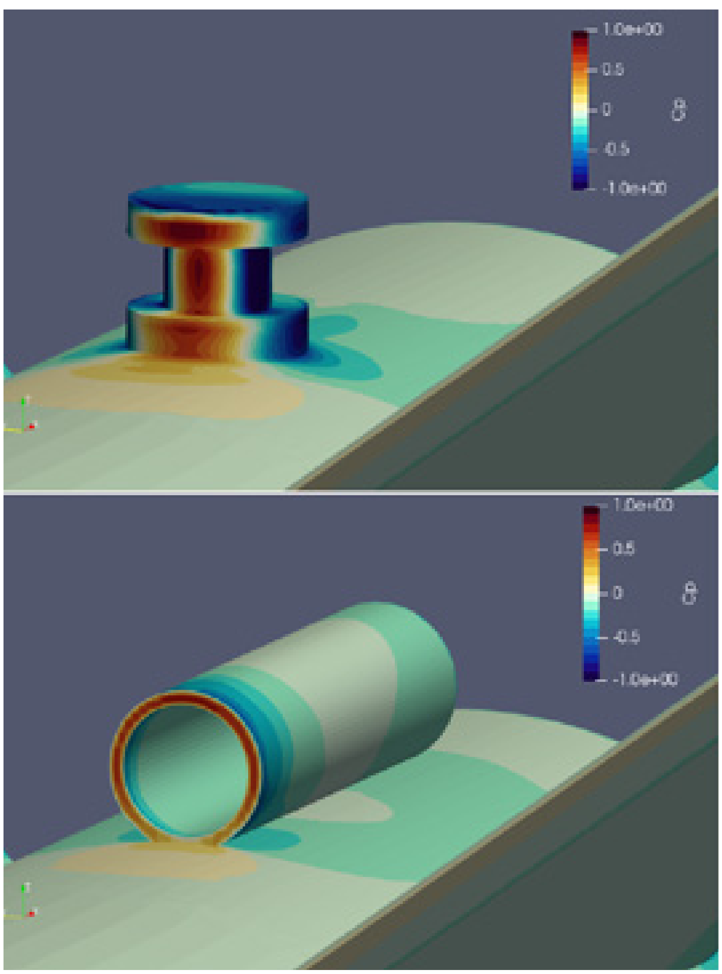
Figure 1 shows a 54mm minimum diameter (MD) rocket in my fleet. Adding parasitic drag is counter to the spirit of MD designs, so rocketeers often use a launch tower. Also, screwing a rail button into a minimum diameter airframe is nearly impossible, leaving surface mount lugs and conformal rail guides as the only practical options. To understand the trade-offs in aerodynamic performance, I constructed four CFD variations of the rocket for comparison:

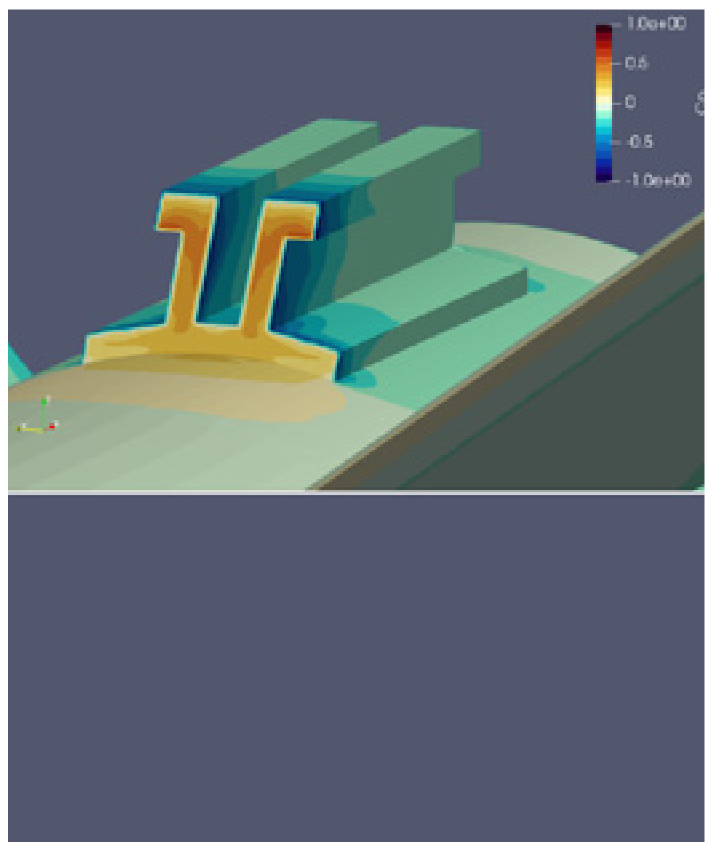
- No launch guides (baseline)
- ¼ inch diameter launch lugs (30 mm long)
- 1010 rail buttons
- Conformal rail guides (e.g. the **Apogee Universal Rail Guide**)

These are CFD models of the complete rocket, and not just the individual appendage in isolation. This shows the power of CFD to simulate real world aerodynamics in full geometric detail. The CAD models were built with the Rocket Workbench and solved with the CfdOF Workbench in FreeCAD.



(Above) Figure 1. 54mm minimum diameter rocket, shown with conformal rail guides





(Above) Figure 2. Pressure coefficient on the aft rail button, conformal rail guide, and launch lug

PEAK OF FLIGHT NEWSLETTER

Computational Fluid Dynamics For Model Rocketry Part 4

Issue 647 / March 11th, 2025

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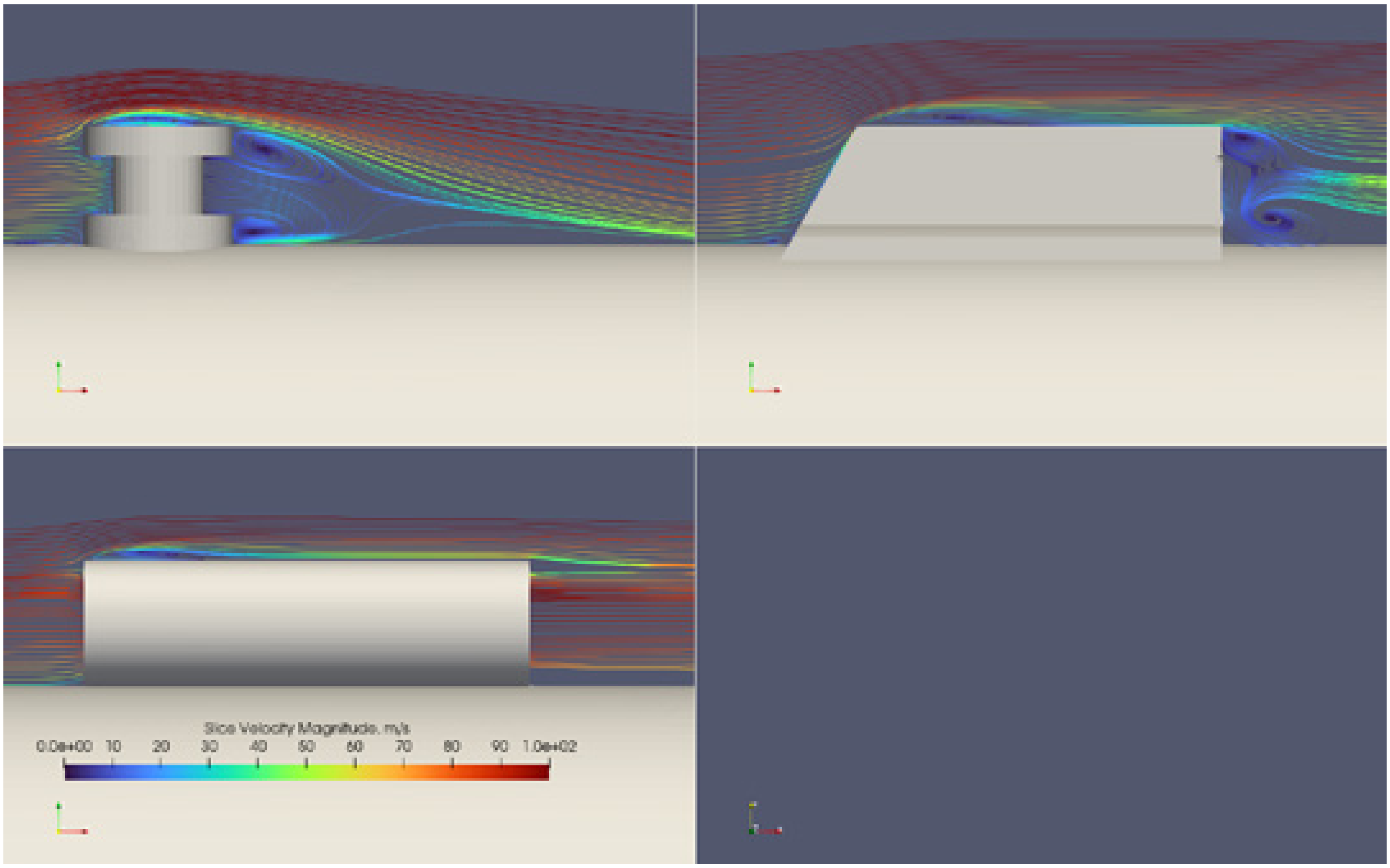
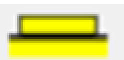


Figures 2 & 3 highlight the aerodynamic pressure on the aft guide and velocity streamlines near the fore guide. With a good mesh resolution, the minute flow structures are captured, such as stagnation points, flow separation, wake vortices, and interaction with the nearby body tube and fins. The button has high pressure on the very front, but it quickly becomes negative as the air flows around the curved surfaces. The conformal launch guide has moderate pressure on the slanted front surface, but it acts over a large area. The button and guide both show a prominent wake behind them. The launch lug looks to be the best performer, with very little disruption of the air flow other than the stagnation pressure on the lug thickness and minor flow separation off the leading edge.

(Above) Figure 3. Velocity streamlines around the forward rail button, conformal rail guide, and launch lug

PEAK OF FLIGHT NEWSLETTER
Computational Fluid Dynamics For Model Rocketry Part 4
Issue 647 / March 11th, 2025
www.ApogeeRockets.com

	Launch Guide Type	FA of Launch Guide (mm^2)	Rocket CD	Launch Guide CD pressure	Launch Guide CD viscous	Total CD	ΔCD
	None		0.489	-	-	0.489	-
	Launch Lugs	21	0.484	0.013	0.003	0.500	0.011
	Rail Buttons	74	0.485	0.024	0.001	0.510	0.021
	Rail Guides	61	0.483	0.024	0.003	0.509	0.020
Ref Area	2552 mm^2						
Ref Velocity	102 m/s						

(Above) Figure 4. Drag breakdown

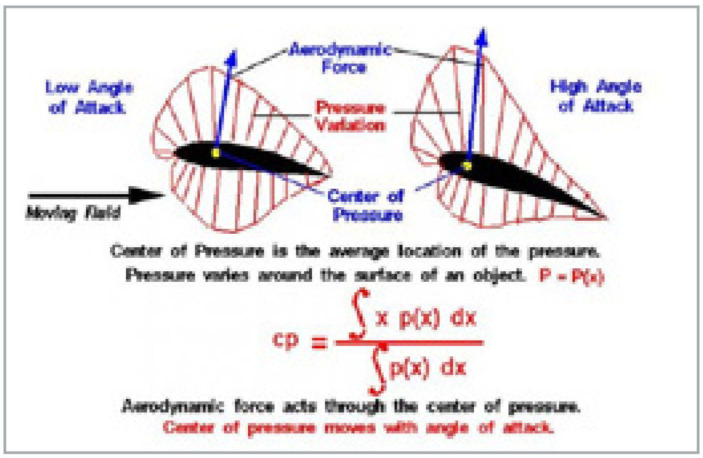
Figure 4 is a table summarizing the drag coefficients at roughly M 0.3. As expected, the launch lugs are the winner, adding just 11 counts of Cd to the rocket. The rail buttons and rail guides are nearly equivalent, adding almost double the drag of the lugs (21 and 20 counts, respectively.) Note that the added drag is not merely the drag force (pressure + viscous) calculated on the appendage itself. The appendage also affects the drag of the rest of the rocket, in fact lowering it. This shows the importance of simulating the entire rocket to capture the interactions between components.

Conformal rail guides are often touted as having less drag than buttons due to a smaller projected frontal area. The frontal area (FA) is given in the table. However, the pressure drag is equivalent between the two. The conformal guide, being longer, has more viscous drag as well. Overall, the rail buttons and rail guides are just about equal on this model.

These appendages add just 2% to 4% drag to this rocket design as simulated with CFD. In my experience, the traditional drag models and software using component superposition are very inconsistent, and often exaggerate the drag increase. CFD data can be used as inputs to Cd overrides in order to create more accurate flight trajectory simulations.

Center of Pressure Calculation

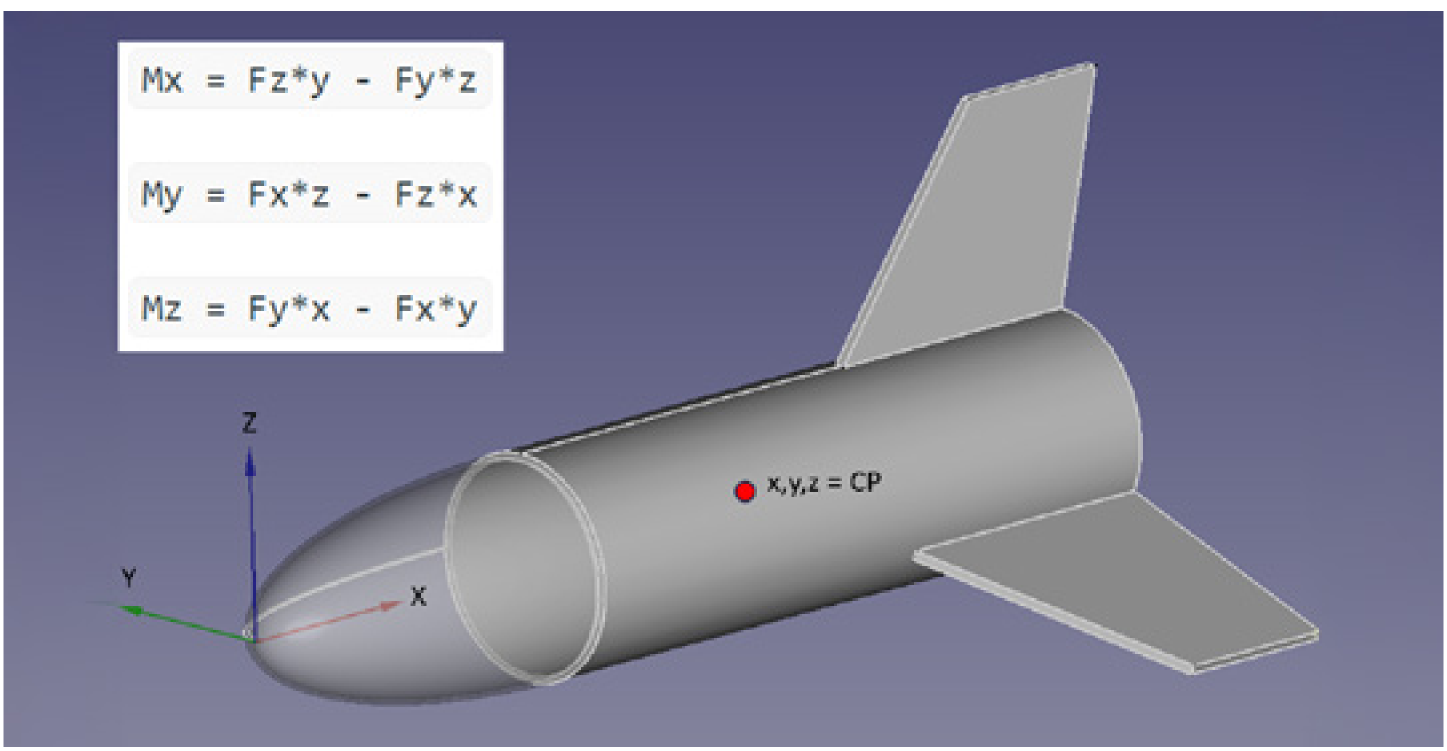
Computing the Center of Pressure (CP) from CFD data is more complicated than drag coefficient and requires some additional hand calculations. While the Barrowman equations were developed around the concept of normal force coefficient slope (CNa), the CFD approach uses the calculated forces and moments themselves. One method is the classic pressure integral as given by the NASA beginners guide to aeronautics. See **Figure 5.** The cp will be the x distance along the body centerline that corresponds to the average pressure location. The image portrays a 2D airfoil, but the integrals can be applied over 3D CFD surfaces as well. The mathematics can be solved in ParaView software using the Calculator and Integrate Variables filter.



(Above) Figure 5. Integral form of CP from NASA website

However, the viscous shear stress vector also contributes to real rocket forces and becomes more significant as the rocket gets longer. This is not accounted for in **Figure 5**. So, the preferred method to compute CP is through moment summation and noting that the CP is defined as the point where all moments vanish. Only the axial and normal forces will generate moments about the principal axes. **Figure 6** shows us the moment equations for the rocket in 3D space.

(Below) Figure 6. Moment equations for CP determination



The components of the F and M vectors are calculated by CFD and written to data files. The goal is to solve for the coordinate x,y,z which will be the center of pressure. This appears easy enough, as there are 3 equations and 3 unknowns. However, this is where the abstract nature of CP comes into play. The center of pressure is not a point, but rather a plane. Thus, there are an infinite number of solutions to the system of equations in **Figure 6.** So, some constraints need to be imposed to make the equations tractable.

We will assume symmetry and that the CP lies on the rocket centerline, making y = z = 0. Also, when the rocket is flying at an angle of attack in the x-z plane, only the pitching moment about the y-axis is relevant. The equations then reduce to as follows:

$$x = \frac{-M_y}{F_z}$$

(Above) Figure 7. CP equation after simplifying assumptions. Applicable to angles of attack greater than zero

In this equation, x is the CP location measured from the tip of the nose cone. **Fig.7** applies to all angles of attack greater than zero.

As angle of attack (α) approaches zero, both My and Fz approach zero. This presents a problem, as x becomes indeterminate. We can use l'Hôpital's rule that allows for evaluating limits of indeterminate forms using derivatives. CP is calculated as follows:

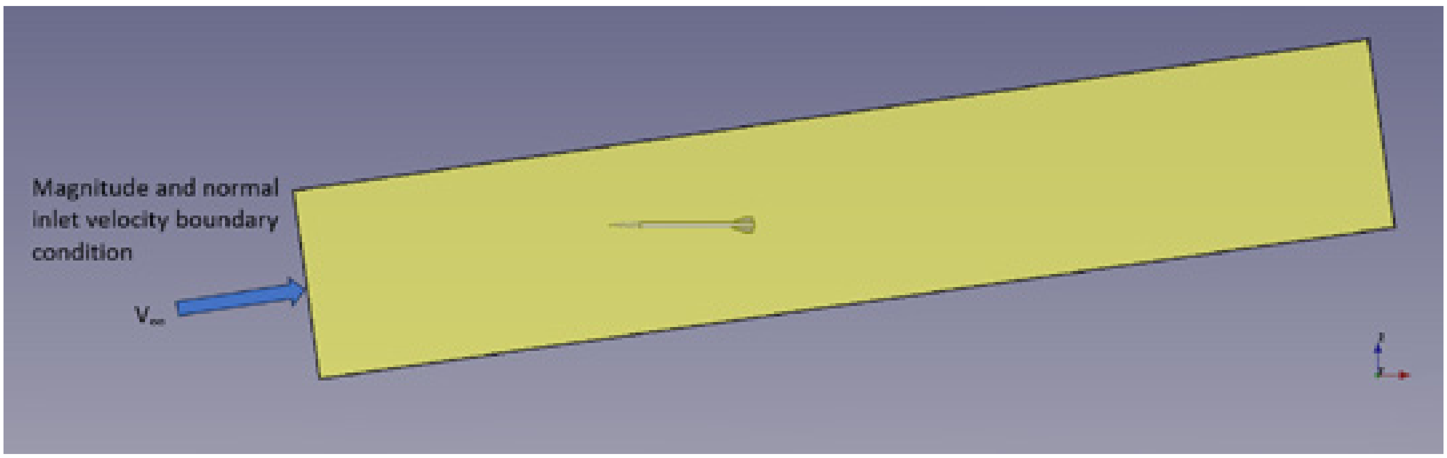
$$x = \left.\frac{\frac{-\partial M_y}{\partial \alpha}}{\frac{\partial F_z}{\partial \alpha}}\right|_{\alpha = 0}$$

(Above) Figure 8. CP equation when angle of attack = zero

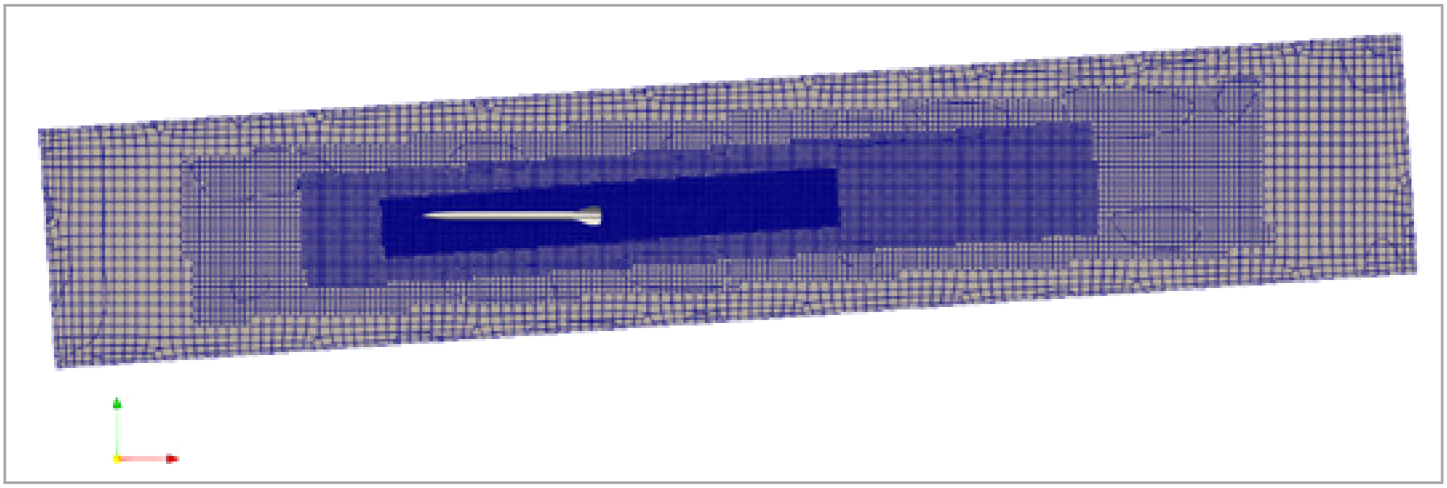
Figure 8 says the CP location is found by using the partial derivatives of My and Fz with respect to the angle of attack, and both evaluated at zero. When put in non-dimensional aerodynamic coefficient form, the force and the moment terms then become CNa and CMa, respectively.

To generate these derivatives, we need to run the CFD model at multiple angles of attack to create Fz and My curves vs. alpha. You may immediately think to rotate the rocket about the y-axis to the desired angle. Rotating the fluid domain an equal and opposite amount can be a better approach, as the rocket stays in the original coordinate system, making it easier to calculate the normal forces and CP location along the rocket (x) axis without any additional trigonometry. Also, specifying the inlet velocity as a constant magnitude and normal is easier than figuring out cartesian components each time the AOA changes. See **Figure 9.**

(Below) Fig. 9. Rotated CFD domain for angle of attack sim.



PEAK OF FLIGHT NEWSLETTER
Computational Fluid Dynamics For Model Rocketry Part 4
Issue 647 / March 11th, 2025
www.ApogeeRockets.com

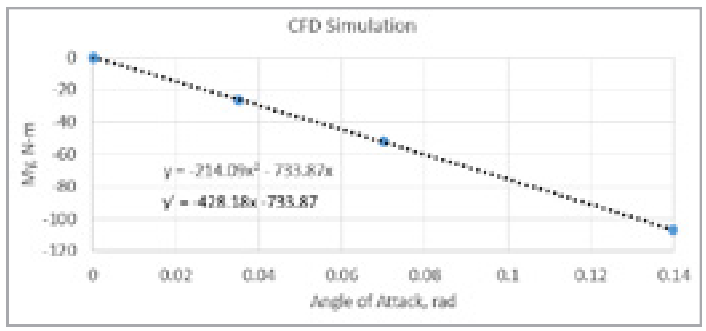


When rotating the domain for small angles of attack, say less than 10 degrees, I will leave the domain size and volume mesh refinements the same as in the zero AOA case. For larger angles you may want to consider increasing the domain cross section (to reduce blockage effect) and to align the mesh wake refinements with the flow direction as in **Figure 10.**

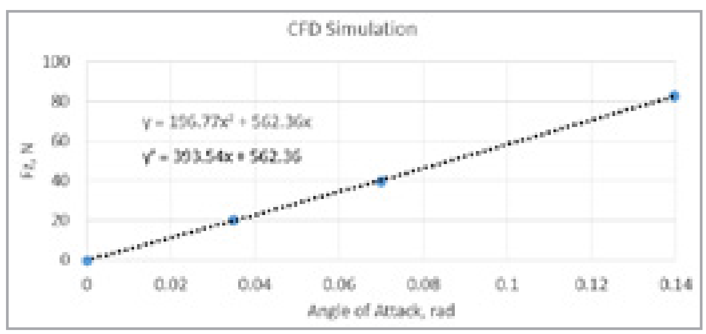
I like to use a 2nd order polynomial for curves of Fz and My vs. angle of attack (A.O.A). At least three points are needed to fit the curve. One point is already known at 0,0. I then choose a few more small angles of attack, like 2, 4, and 8 degrees and run CFD simulations of those cases. After plotting this data, I then fit least squares curves through them. (It is often assumed that force and moment are linear at small angles of attack, so in that case, only two points are sufficient.)

Figures 11 & 12 are plots of Fz and My vs. A.O.A in radians for the 75 mm HPR CFD model shown in **Figure 10** flying at Mach 0.3. The trendline equation is given along with the first derivative.

(Above) Figure 10. Mesh refinement volumes rotated along with the domain



(Above) Figure 11. Pitching moment vs. angle of attack

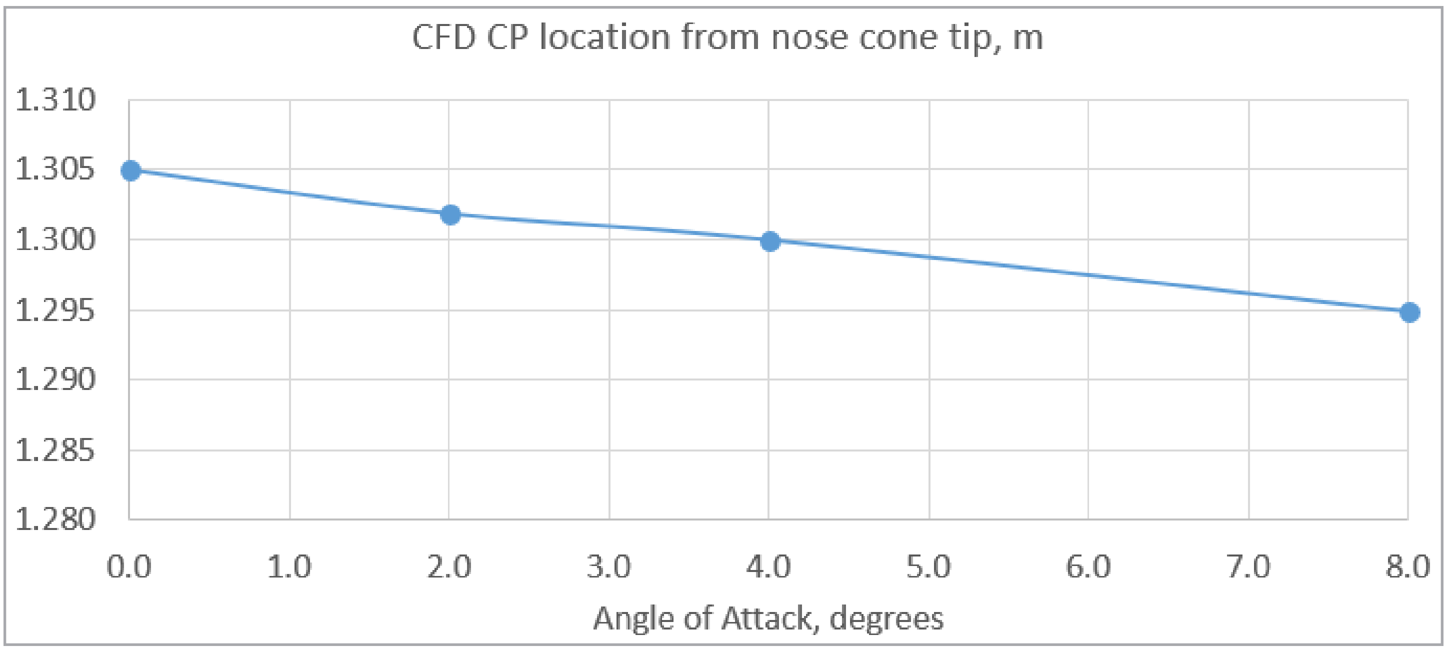


(Above) Figure 12. Normal force Fz vs. angle of attack

Evaluating the derivatives at zero per Figure 8 yields the CP location at zero AOA, shown in **Figure 13:**

$$x = -\frac{-733.87}{562.36} = 1.305\ m$$

(Above) Figure 13. Center of pressure x-coordinate at zero angle of attack



(Above) Figure 14. CFD CP vs. angle of attack

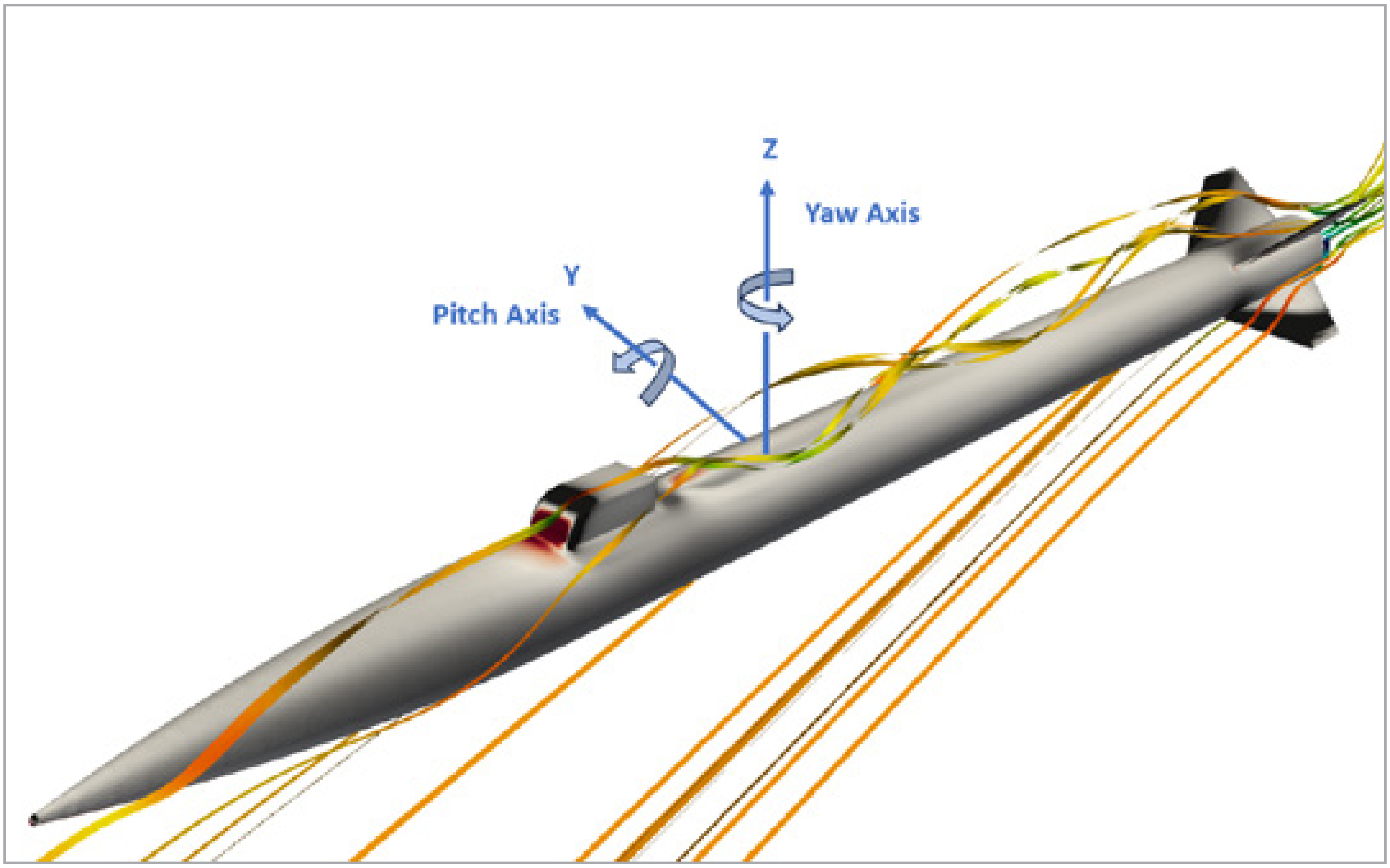
Figure 14 is a plot of CP location for the four angles evaluated. As expected, the CP moves forward as AOA is increased. The CP predicted by this method with CFD data will usually be more rearward than Barrowman estimations, due to fin thickness, vortices, and skin friction, which are all stability enhancing. These items and others are neglected in the Barrowman assumptions. In the case of this model at zero AOA, the Barrowman CP is 0.9 calibers forward of the CFD location, and the RockSim CP is 0.2 calibers forward of the CFD location.

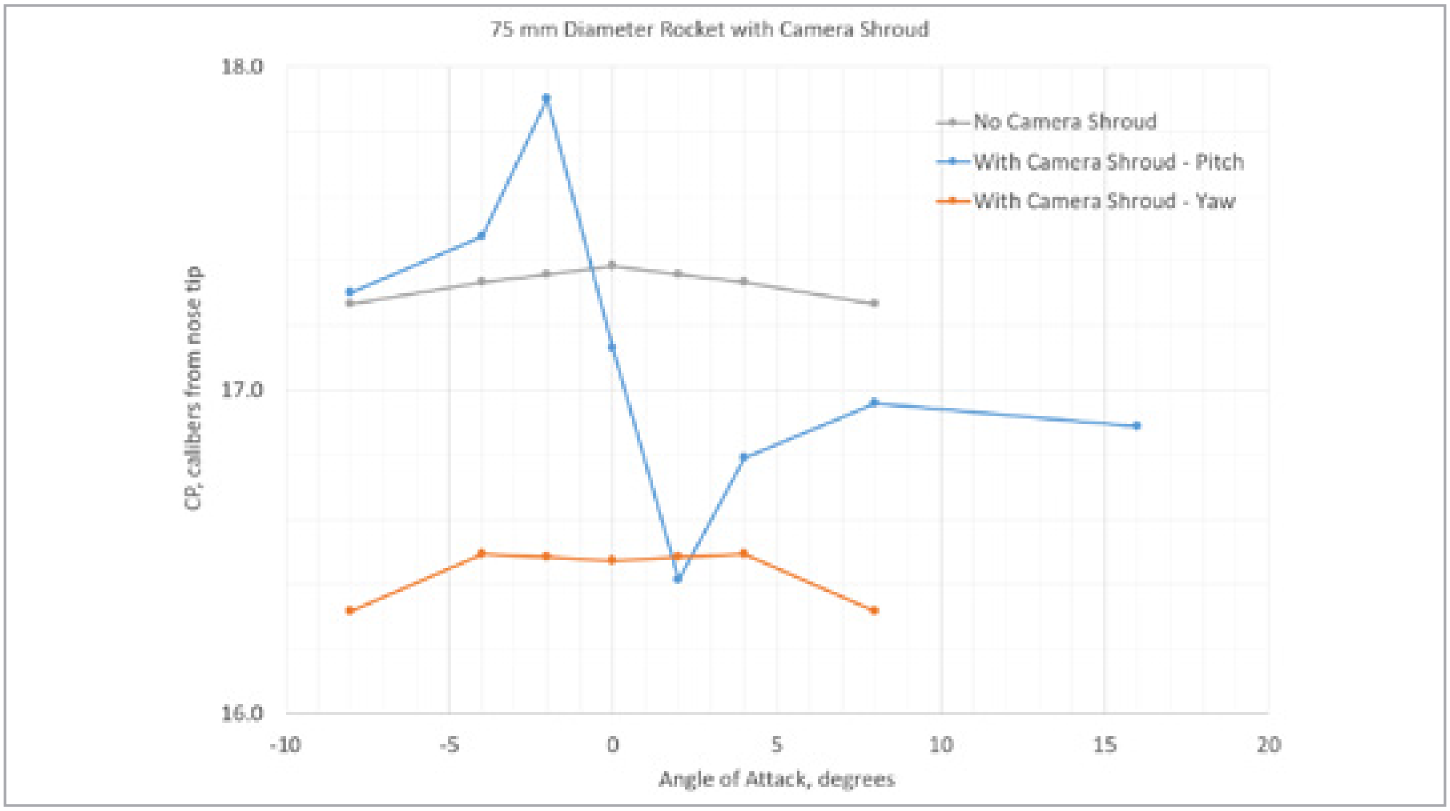
External Camera Stability Analysis

An interesting question often arises when attaching a camera to the outside of the rocket near the nose cone. "Does the camera decrease stability?" Since the camera or its shroud may act like a fin, it is fair to think that the CP may move forward. The shape of a camera is not a fin, however, and there is no Barrowman equation that can model its aerodynamics. That is where CFD comes in. Any arbitrary geometry is fair game for a CFD airflow simulation.

(Below) Figure 15. External camera shroud

Figure 15 shows the 75mm rocket CFD model with a camera shroud attached and flying at an angle of attack. I mocked up a simple shroud in CAD that is similar to those that are 3D printed and house a keychain camera. It is mounted between two fins for an unobstructed downward view. It has a rounded nose and radiused front corners for reduced drag. Still, the front face of the shroud creates a high-pressure stagnation zone and generates a rotating wake behind it, disrupting the airflow downstream.

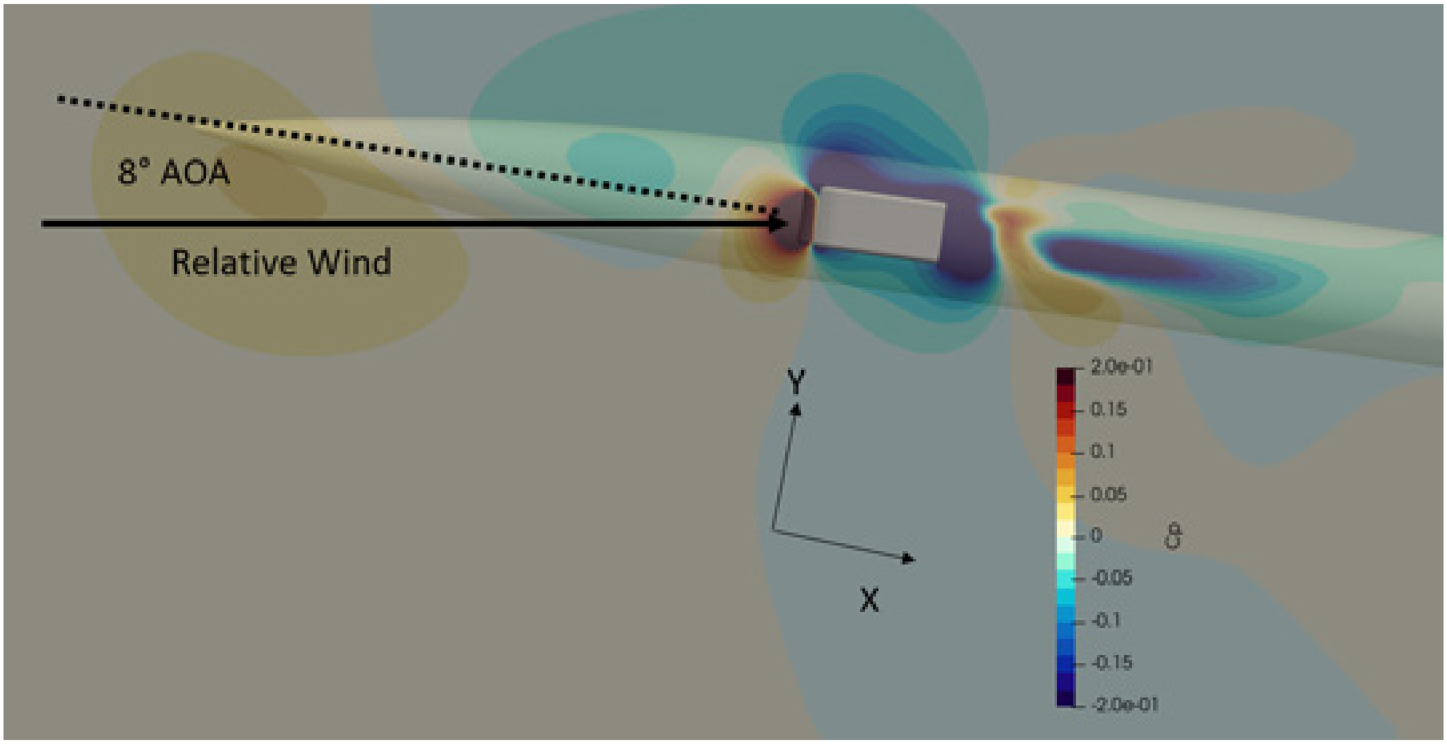




(Above) Figure 16. Camera shroud CP comparison

Attaching the camera shroud to the airframe creates an asymmetry condition that complicates the calculations. The forces, moments, and resulting CP may be different depending on how the rocket is oriented when flying at an angle of attack. More than one axis of rotation needs to be considered, and an infinite number are possible. For this example, I will consider just the two primary axes for pitch and yaw as these should hopefully bookend the range of center of pressure.

I ran several AOA conditions and plotted the resulting CP location in **Figure 16**. With no camera shroud, the CP moves forward with angle of attack in a linear fashion and is symmetric about zero. With the camera attached, and the rocket angled in the pitch direction, the CP movement is very aggressive at the small angles. The CP can increase or decrease depending if the camera shroud is pitched into the oncoming airflow or pitched away from it. Symmetry exists about AOA = 0, but mirrored between the 2nd and 4th quadrants of the graph. At zero angle of attack, the CP shift in the pitch direction due to the camera is just 0.3 calibers.



(Above) Figure 17. The Pressure contours on the shroud in yaw condition

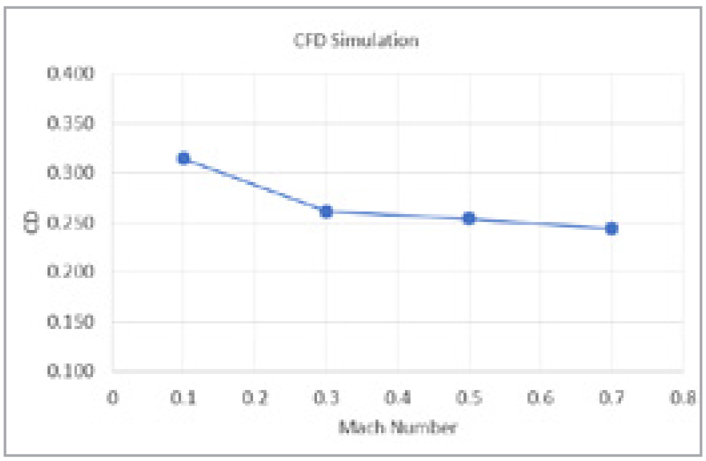
In the yaw direction, the behavior is much different. The CP location does not begin moving until beyond 4°. The CP shift due to the camera is greater, about one full caliber forward. This makes sense, as the relative wind hits the camera shroud more broad side, generating a fin effect. This can be seen in **Figure 17** with the positive and negative pressure differential around the shroud. Very negative pressure on the leeward side is pulling the shroud in the +Y-direction and forcing the rocket to yaw even more. When designing for stability analysis, we should always use the worst-case condition. With the camera attached, the worst case is when the rocket is at an angle of attack in its yaw axis.

Overall, the camera shroud does not move the CP forward dramatically on this rocket. In fact, in some orientations, the CP can move rearward during flight. If the static stability margin without camera is at least 1 caliber per the rule of thumb, then adding the appendage will likely not be a problem. The mass of the camera and shroud, in this far forward position, also pulls the CG forward, helping stability. All this may explain why rocketeers add external cameras of many shapes and sizes with no ill effects on the flight.

RockSim Pro Override Tables

If you use RockSim Pro, you can override both drag coefficient AND center of pressure for better flight simulations. The overrides are not just single values, but rather functions of Mach Number and angle of attack. The data must come from an external source, such as flight testing, wind tunnel simulation, or as in this case, CFD.

Figure 18 is a Cd vs. Mach Number curve for a low-drag rocket that I simulated in CFD. The design includes a custom nose cone and bi-convex fin sections, both of which are not supported in RockSim. So, CFD is the best available tool to model this rocket's aerodynamics. Four speeds were evaluated at Mach 0.1, 0.3, 0.5, and 0.7. The resulting piecewise linear curve looks reasonable for subsonic speeds.

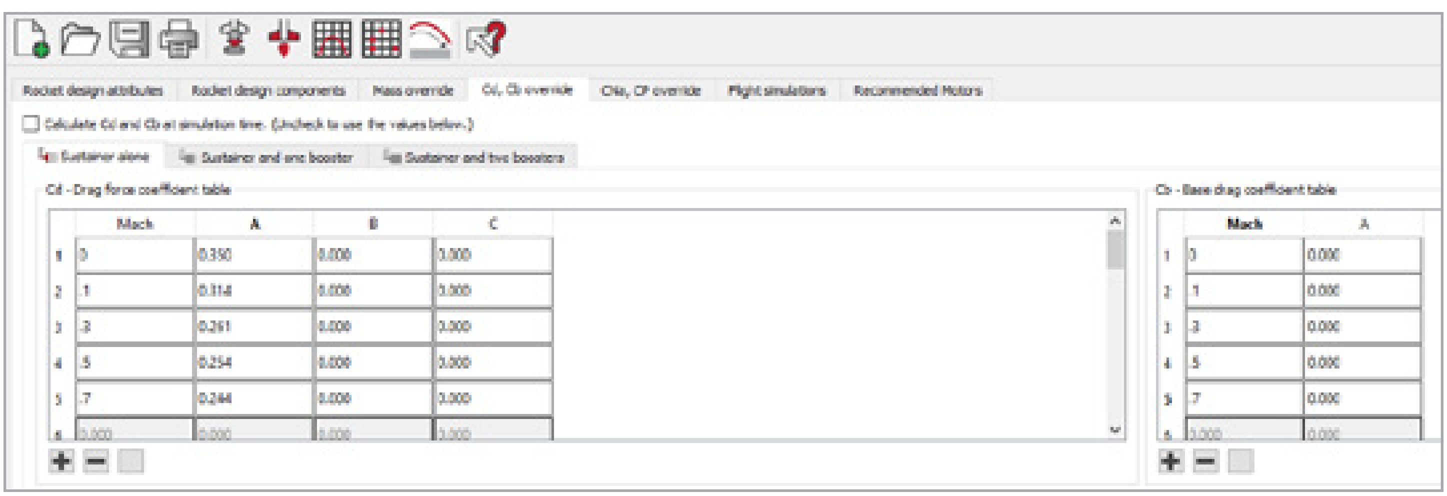


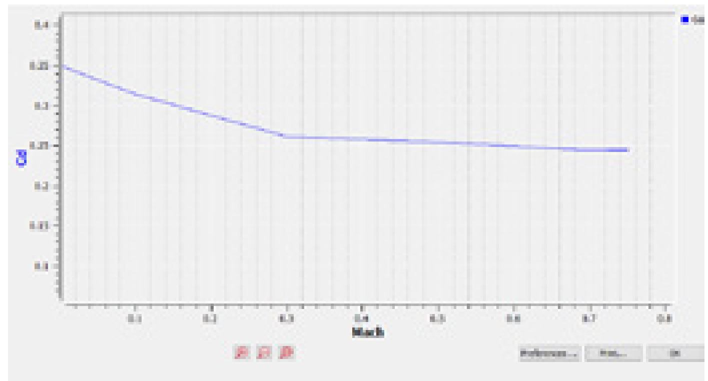
(Above) Figure 18. Cd vs. Mach Number from CFD simulation

Figure 19 shows the Cd, Cb Override table in RockSim Pro. Cb is used to adjust the base drag coefficient when the rocket is thrusting vs. coasting. It is best to leave Cb as zero if good information is not available, as in this case. A, B, C are coefficients for 2nd order polynomials of the force vs. angle of attack in radians. For Cd at each Mach Number, we can specify:

Cd = A + B*AOA + C*AOA2

(Below) Figure 19. Drag override tab in RockSim Pro





(Above) Fig 20. Cd vs. Mach in RockSim Pro flight simulation

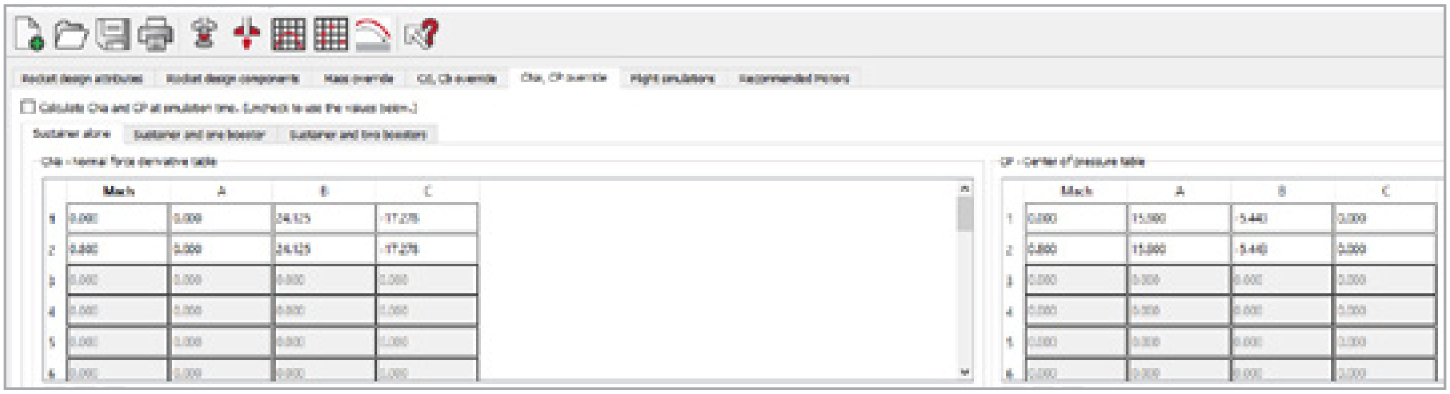
To be honest, I cannot get the B and C coefficients for drag to work as expected in the RockSim Pro flight simulation, so I leave them at zero and use just the intercept, A. Since the rocket spends little time at non-zero angles attack, this is a reasonable assumption. In the table, I input my four values of Cd from CFD, along with an extrapolated value at Mach = 0 to help the linear interpolation when speed is less than M 0.1.

After running the flight simulation in RockSim Pro, you can verify that the override values were used correctly by plotting the graph of Cd vs. Mach as in **Figure 20.** This plot agrees with my Cd curve in **Figure 18.**

RockSim Pro is the only hobby software that I know of that allows you to override the CP location. This is perfect for using CFD-generated stability data of designs beyond the Barrowman assumptions. **Figure 22** shows the override tables that follow the same form of an angle of attack polynomial at each Mach Number. The tables ask for CP (in calibers) on the right and CNa -Normal force derivative on the left. I believe CNa is a typo, and the table actually requires CN – Normal force coefficient. Using the CFD coordinate system discussed earlier with symmetric normal forces, CN can be defined as follows in **Figure 21:**

$$CN = \frac{F_z}{\frac{1}{2} A \rho_\infty V_\infty^2}$$

(Above) Figure 21. Normal force coefficient



(Above) Fig. 22. Center of Pressure override tab, RockSim Pro

Figures 23 and 24 are test cases I created for CN and CP vs. angle of attack. Four angles were evaluated up to 30° to generate curves by least squares fitting. A 2nd order fit for CN is a good assumption, and a straight line was fit to the CP data. The coefficients were applied to the A, B, and C table inputs in **Figure 22.** I used the same curves from 0.0 to 0.8 Mach, as CP location does not change too much in the subsonic range.

After running the flight simulation in RS Pro, you can again plot the graphs of these parameters to verify that the override inputs were used correctly. See **Figure 25.** CP is plotted in millimeters, but the values correctly correspond to the caliber units provided.

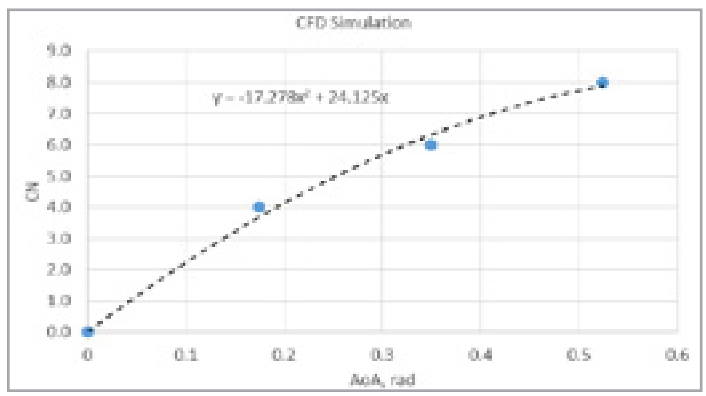


Figure 23. CN vs. angle of attack from CFD simulation

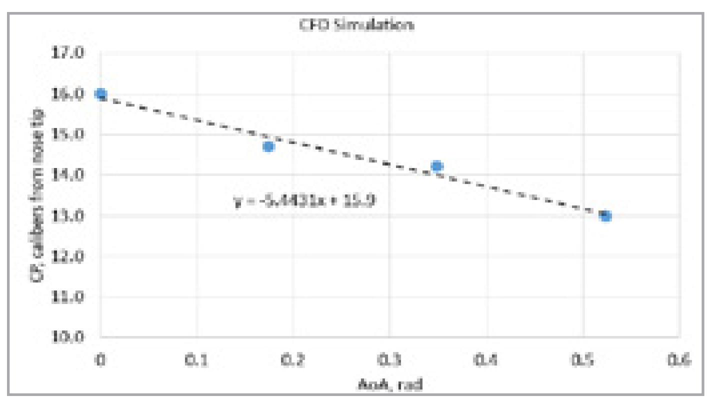


Figure 24. CP vs. angle of attack from CFD simulation

Conclusion

This article presented a few applications of Computational Fluid Dynamics to aide in model rocket design. These scenarios are not possible in the traditional simulation software due to their unique geometry. CFD, being general purpose and capable in all flow regimes, can provide accurate analyses for a wide range of rocket projects. The CFD results in turn can be inputs to flight simulations with accurate aerodynamics.

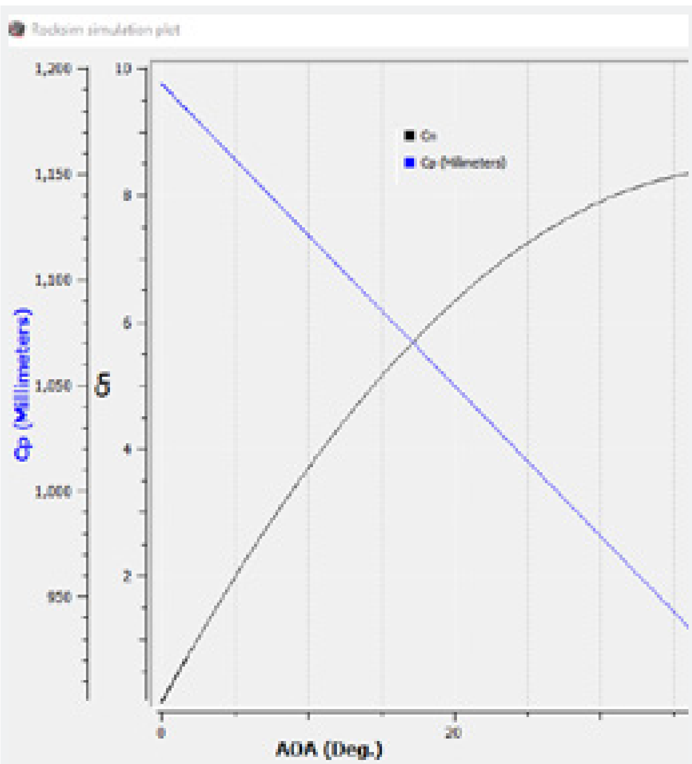


Figure 25. CN and CP vs. angle of attack used in RockSim Pro flight simulation

About the Author:

Ken Karbon is a rocketeer from Michigan. He is a retired engineer from the auto industry where he specialized in CFD and aerodynamics.

PEAK OF FLIGHT NEWSLETTER
Issue 647 / March 11th, 2025
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We are always looking for quality articles to publish in the *Peak-of-Flight* newsletter. Please submit the “idea” first before you write your article. It will need to be approved first.

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Always include your name, address, and contact information with all submissions. Including best contact information allows us to conduct correspondence faster. If you have questions about the current disposition of a submission, contact the editor via email or phone.

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We prefer articles that have at least one photo or diagram for every 500 words of text. Total article length should be between 2000-4000 words and no shorter than 1750 words. Articles of a “how-to” nature are preferred (though other types of articles will be considered) and can be on any rocketry topic: design, construction, manufacture, decoration, contest organization, etc. Both model rocket and high-power rocket articles are accepted.

CONTENT WE ARE NOT LOOKING FOR

We don't publish articles like "launch reports." They are nice to read, but if you don't learn anything new from them, then they can get boring pretty quick... Example: "Bob flew a blue rocket on a H120 motor for his certification flight." As mentioned above, we’re looking for articles that have an educational component to them, which is why we like “how-to” articles.

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Here are some of the common articles that we reject all the time, because we’ve published on these topics before:

- How to get a L1, L2, or L3 Cert
- Building cheap rockets and equipment (pads & controllers)
- How to 3D print parts, or a Rocket Kit
- How to Build a cheap Rocket Kit
- Getting Back Into Rocketry After a Long Hiatus

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Articles may be submitted by emailing them to the editor. Article text can be provided in any standard word processor format, or as plain-text. Graphics should be sent in either a vector format (Adobe Illustrator, SVG, etc.) or a raster format (such as jpg or png) with a width of at least 600 pixels for single column images or 1200 pixels for two-column images. It is preferable for images to be simple enough to be readable in a two-column layout, but special layouts can be used.

Send the images separately via email as well as show where they go by placing them in the word processor document.

ACCEPTANCE

Submitted articles will be evaluated against a rubric (available here on our website). All articles will be evaluated and the results will be sent to the author. In the evaluation process, our goal is to ensure the quality of the content in *Peak-of-Flight*, but we want to publish your article! Resubmission of articles that do not meet the required standard are heavily encouraged.

ORIGINALITY

All articles submitted to Peak-of-Flight must not run in another publication before inclusion in the *POF* newsletter, but it may be based on another work such as a prior article, R&D report, etc. After we have published and paid for an article, you are free to submit them to other publications.

RATES

Apogee Components offers **$300** for a quality-written article over 2,000 words in length. Payment is pro-rated for shorter articles.

WHERE WILL IT APPEAR?

These articles will mainly be published in our free newsletter, *Peak-of-Flight*. Occasionally some of the higher-quality articles could potentially appear in one of Tim Van Milligan's books that he publishes from time to time.


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