PEAK OF FLIGHT NEWSLETTER

Issue 617 / January 16th 2024

APOGEE COMPONENTS
www.ApogeeRockets.com
4960 Northpark Dr, Colorado Springs CO 80918
Ph# 719-535-9335

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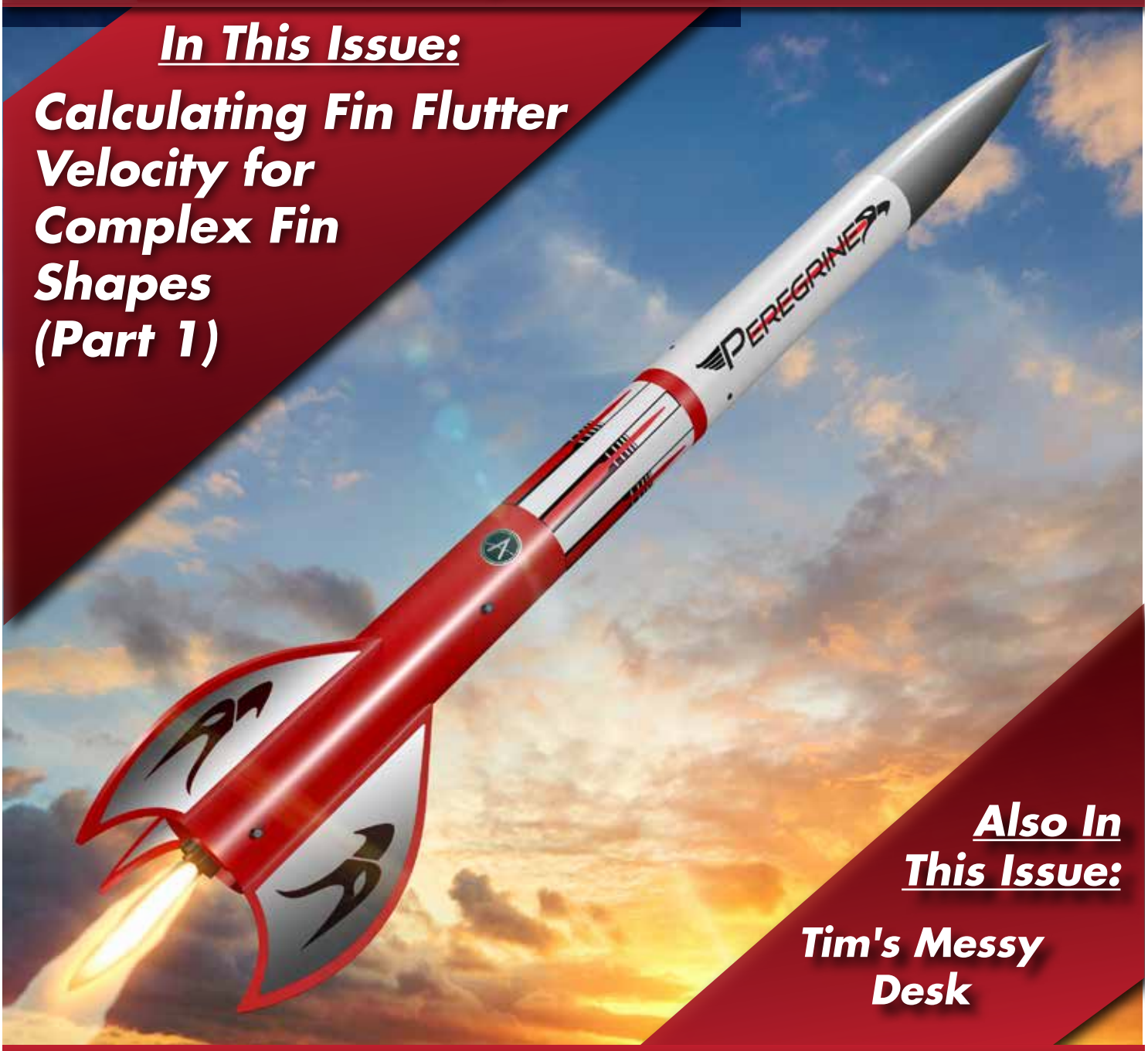

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Calculating Fin Flutter Velocity for Complex Fin Shapes (Part 1)

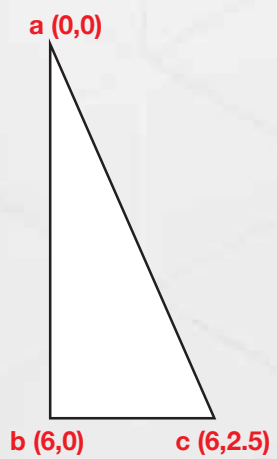
By John K. Bennett

In *Peak of Flight* Issue #615, I described how to estimate the fin flutter velocity for trapezoidal and elliptical fin shapes. This follow-on two-part article describes how to handle triangular, multi-sided, and other more complex fin shapes. The original article should be read for this one to make better sense. In most of the examples shown, we will use arbitrary units of length, without concerning ourselves about the unit system in use.

When estimating flutter velocity for a complex fin design, the fin properties that are most likely to be challenging to calculate include **Fin Area, Cx** (the axial distance from the front of the fin to the fin centroid), and possibly **tip chord length**. Let's examine how these values can be calculated for fin shapes that are not trapezoidal or elliptical.

Triangular Fins

Although there are explicit formulae for the area and centroid of a triangle (see below), we don't have to use them. Since a triangle can be considered as a degenerate form of trapezoid, the trapezoidal equations in the original article and spreadsheet work fine for triangular fins; we just need to set the tip chord length to zero. This will also make λ equal to zero. The trapezoidal equations will produce correct results for triangular fins once this is done. Let's prove this to ourselves. Consider the following triangular fin:



The area of a triangle = ½ **base** * **height**, or in this case, **3*2.5 = 7.5**. The area of a trapezoid with a zero-length tip chord reduces to the same formula:

$$Area = Height \times \frac{\cancel{Tip\ Chord\ Length} + Root\ Chord\ Length}{2}$$

As we will see below, the centroid of a triangle given its vertices is just the average of each of the vertex coordinates, i.e.,

$$C_x = \frac{\left(V1_x + V2_x + V3_x\right)}{3}$$

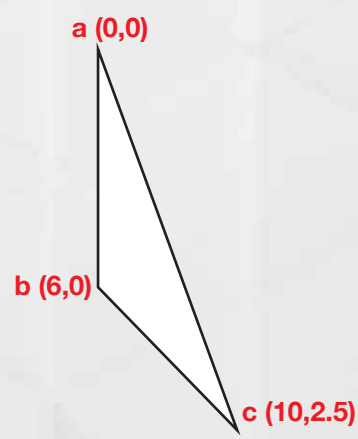
C_x = (0 + 6 + 6) / 3 = 4.

If we use our formula for the centroid of a trapezoid with the tip chord set to zero (note that m, the sweep length, is the **x** coordinate of the **c** vertex in the triangle shown above),

$$C_x = \frac{(2 \times TC \times m) + TC^2 + (m \times RC) + (TC \times RC) + RC^2}{3(TC + RC)}$$

we get C_x = ((0) + (0) + (6*6) + (0) + (6*6)) / (3*6) = 4, the same answer we obtained above.

This method also works when the triangle is irregular. Consider the following (probably not very good) fin design:



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Newsletter Staff
Writer: John K. Bennett
Editor: Tim Van Milligan
Layout: Ryan Conway

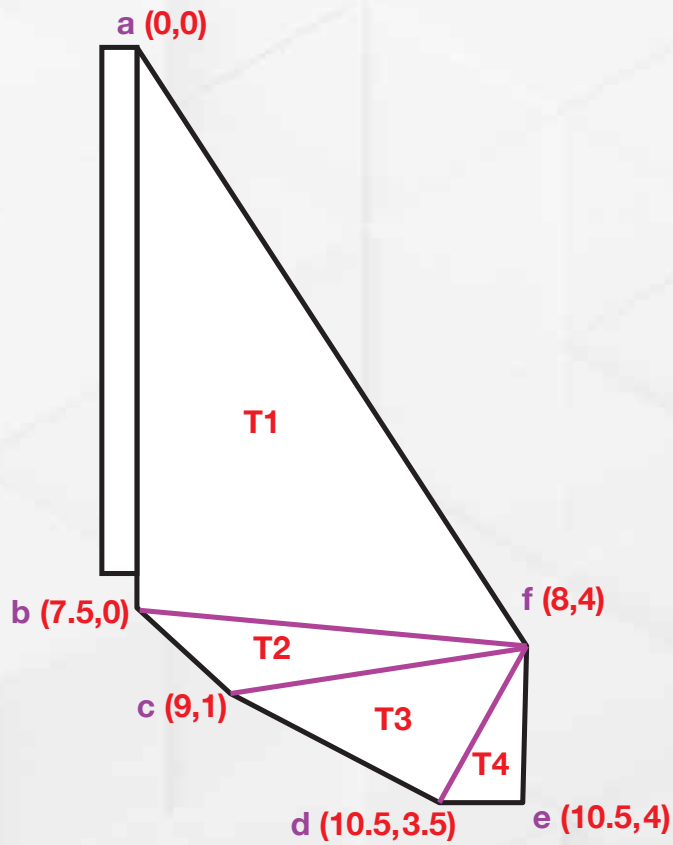
In this case, C_x calculated using the triangle formula is **(0 + 6 + 10) / 3 = 5.33**. C_x calculated using the trapezoid formula (with TC set to zero) is = **((0) + (0) + (10*6) + (0) + (6*6)) / (3*6) = 5.33**.

To summarize, for triangular fins we can calculate V_f using the fin flutter velocity spreadsheet in the usual way. We only need to set the tip chord length to zero. The fin sweep length is just the **x** coordinate of vertex **c** (6 and 10 in our two examples).

Triangular fins such as these are also easy to simulate. RockSim and OpenRocket both provide the means to create custom fins by entering a set of points. In this case, we would enter the vertices **a**, **b**, and **c**. See *Peak of Flight* Issue #488 (February 5, 2019)[3] for an example of how to do this in RockSim.

Other Simple Polygon-Based Fin Shapes

For more complex fin shapes, we can use a method called "geometric decomposition." This method divides the fin into a set of geometric objects (typically triangles, rectangles, or circles) that we know how to handle, and then combines the results. The easiest way to employ geometric decomposition is to assign **(x, y)** coordinates to each vertex of the fin polygon. For example, consider the swept fin pictured to the right.



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Calculating Fin Flutter Velocity for Complex Fin Shapes (Part 1)

By John K. Bennett

The fin polygon vertices are labeled **a**, **b**, **c**, **d**, **e**, and **f**. We first determine the coordinates for each vertex (assigning (0, 0) to the forward most vertex toward the nosecone to simplify the calculation). The vertex coordinates come from the fin design itself. Then we divide the fin polygon into a small number of triangles.[4] The resulting four triangles: **abf**, **bcf**, **cdf**, and **def**, are demarked in the figure with purple lines. Let's label these triangles **T1**, **T2**, **T3**, and **T4**, respectively, as shown on the figure. If we calculate the areas of the four triangles, the area of the entire fin is just the sum of these areas. Let's see how this works. From geometry, we know that the area of any triangle, given its three vertex coordinates **(A_x, A_y)**, **(B_x, B_y)**, and **(C_x, C_y)** is:

$$Area = \left| \frac{A_x(B_y - C_y) + B_x(C_y - A_y) + C_x(A_y - B_y)}{2} \right|$$

Using this formula, we can calculate the areas of each of the four triangles are as follows:

$$Area(T_1) = \left| \frac{a_x(b_y - f_y) + b_x(f_y - a_y) + f_x(a_y - b_y)}{2} \right|$$

Area of T1 (abf) = (0(0-4) + 7.5(4-0) + 8(0-0))/2 = 15

$$Area(T_2) = \left| \frac{b_x(c_y - f_y) + c_x(f_y - b_y) + f_x(b_y - c_y)}{2} \right|$$

Area of T2 (bcf) = (7.5(1-4) + 9(4-0) + 8(0-1))/2 = (-22.5+36-8)/2 = 2.75

$$Area(T_3) = \left| \frac{c_x(d_y - f_y) + d_x(f_y - c_y) + f_x(c_y - d_y)}{2} \right|$$

Area of T3 (cdf) = (9(3.5-4) + 10.5(4-1) + 8(1-3.5))/2 = (-4.5+31.5-20)/2 = 3.5

$$Area(T_4) = \left| \frac{d_x(e_y - f_y) + e_x(f_y - d_y) + f_x(d_y - e_y)}{2} \right|$$

Area of T4 (def) = (10.5(4-4) + 10.5(4-3.5) + 8(3.5-4))/2 = (0+5.25-4)/2 = 0.625

The total fin area is therefore **15 + 2.75 + 3.5 + 0.625 = 21.875**. Now that we have the area, we can calculate **C_x**. To do this, we need to find the centroid of each of our triangles (recall that we only need the axial - parallel to the direction of flight - dimension of the centroid), and then calculate their weighted average to determine the fin centroid. Let's start with the triangle centroids. **C_x** of any triangle, given its coordinates, is just the average of the **x** coordinates of its vertices, i.e.,

$$C_x = \frac{(V1_x + V2_x + V3_x)}{3}$$

Therefore:

$T1_{Cx}$ = (0 + 7.5 + 8)/3 = 5.17

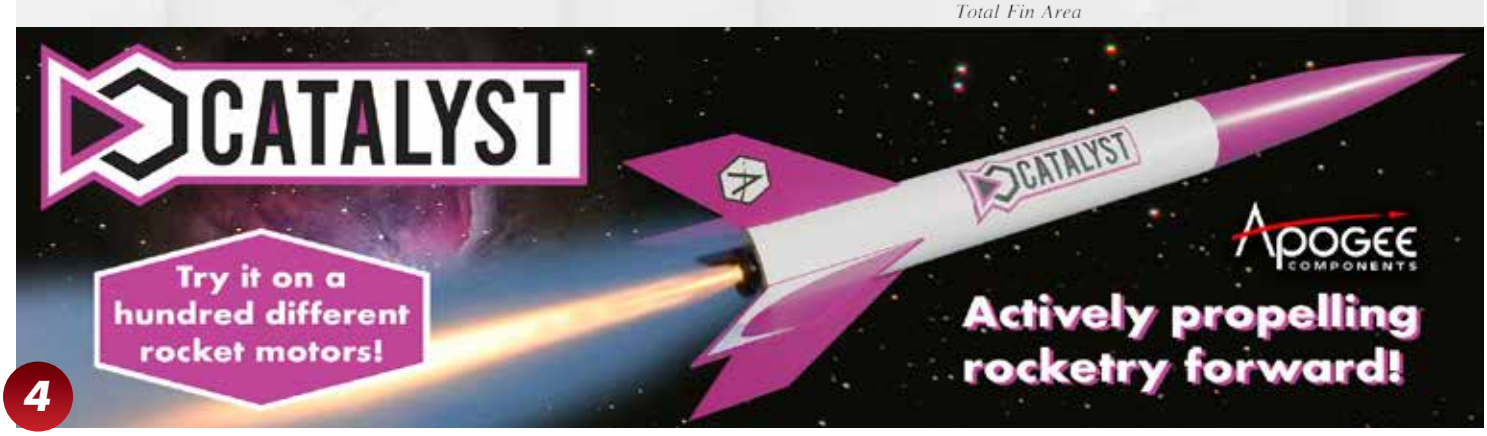
$T2_{Cx}$ = (7.5 + 9 + 8)/3 = 8.17

$T3_{Cx}$ = (9 + 10.5 + 8)/3 = 9.17

$T4_{Cx}$ = (10.5 + 10.5 + 8)/3 = 9.67

To calculate **C_x** of the entire fin, we calculate a weighted average by adding the products of each triangle's **C_x** and the area of that triangle, and then divide the result by the total fin area, as follows:

$$C_x = \frac{((T1\,C_x \times T1\,Area) + (T2\,C_x \times T2\,Area))}{Total\ Fin\ Area} + \frac{(T3\,C_x \times T3\,Area) + (T4\,C_x \times T4\,Area)}{Total\ Fin\ Area}$$



Therefore, **C_x = ((5.17 * 15) + (8.17 * 2.75) + (9.17 * 3.5) + (9.67 * 0.625)) / 21.875**

= ((77.55) + (22.47) + (32.1) + (6.04)) / 21.875

= 6.31

Now we can calculate **ε** using the formula (recalling that ε is a measure of distance expressed as a fraction of the whole root chord):

$$\varepsilon = \left(\frac{Cx}{RC}\right) - 0.25$$

ε = 6.31/7.5 – 0.25 = **0.59**

Armed with these values, we can now calculate $\mathbf{V_f}$ in the usual way. Recall that the fin sweep length is just the **x** coordinate of vertex **f** (8 in this case).

Entering these data into the fin flutter velocity spreadsheet (overriding the values for $\mathbf{C_x}$ and **Fin Area** to use the values calculated above) allows us to estimate the flutter velocity for our polygonal fin.

Polygonal fins such as these are also easy to simulate. As before, RockSim and OpenRocket both provide the means to create custom fins by entering a set of points. In this case, we would enter the vertices **a**, **b**, **c**, **d**, **e**, and **f**. Again, see *Peak of Flight* Issue #488 (February 5, 2019)[3] for an example of how to do this in RockSim.

Complex Fins with Conic Shapes

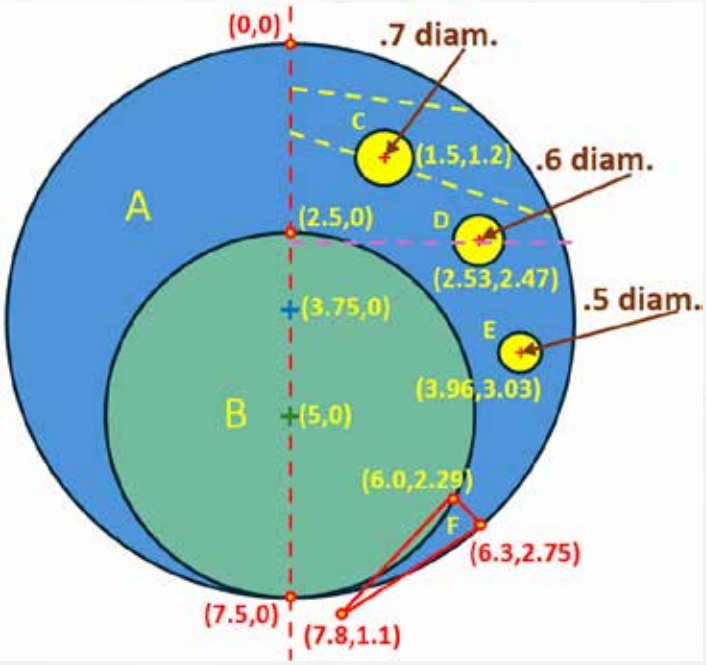
Geometric decomposition is a powerful tool, which can be applied in either an additive (as in the previous example) or a subtractive manner, as we will see in the next example. If you have ever designed a part to be 3D printed by joining and cutting different geometric shapes, that is the same process we will use to obtain the area and centroid of a complex fin.

This example will explore how to estimate the flutter velocity of a “bat wing” fin with holes. For purposes of this example, we will ignore the question of the flight-appropriateness of such a fin, and just go with “hey, they look really cool.” We will also ignore any aerodynamic concerns other than estimation of flutter velocity.

Consider the following fin shape:

Let’s see how we can analyze this fin using geometric decomposition. We start by looking closely at how the fin image might be constructed (this approach was, in

fact, the one used in Fusion 360 to design the fin depicted above), as shown in the (not quite to scale) figure below.



This figure shows two large circles (**A** enclosing **B**), three small circles (**C**, **D**, and **E**), and triangle **F**. The red dashed line bisects the two large circles. The two dashed yellow lines represent the quarter chord and half chord lines. We will come back to the dashed purple line in a bit. The coordinates show the location of all relevant points (color has no significance other than visibility). Triangle **F** is intended to represent the "straightened out" small, curved triangle at the bottom of the figure with an equivalent area triangle. This is just to save us a bunch of tedious math for a very small part of the problem. After we size triangle **F**, we can "cut off" the blue arced segment from our fin (and from further consideration).

Calculation of Fin Area

Upon examination, we see that our bat fin image can be constructed by taking the right half of circle **A**, and subtracting the right half of circle **B**, as well as circles **C**, **D**, and **E**, and the triangle **F**. This is exactly how we can calculate the area of our fin, as follows:

The area of the right half of circle **A** is **(πr^2)/2 = (π*3.75*3.75) / 2 = 22.1**

The area of the right half of circle **B** is **(πr^2)/2 = (π*2.5*2.5) / 2 = 9.82**

The area of circle **C** is **(πr^2) = π*0.35*0.35 = .38**

The area of circle **D** is **(πr^2) = π*0.3*0.3 = .28**

The area of circle **E** is **(πr^2) = π*0.25*0.25 = .2**

We use the formula for the area of a triangle given its vertices to calculate the area of triangle **F**:

$$Area = \left| \frac{A_x\left(B_y - C_y\right) + B_x\left(C_y - A_y\right) + C_x\left(A_y - B_y\right)}{2} \right|$$

The area of triangle **F** is **(7.8(2.75-2.29) + 6.3(2.29-1.1) + 6(1.1-2.75))/2 = (3.59+7.5-9.9)/2 = 0.6**

Combining these terms, the **total area of the fin = 22.1 - 9.82 - .38 - .28 - .2 - 0.6 = 10.82**

Calculation of C_x

To calculate **x** dimension of the fin centroid, we need to first calculate C_x (the **x** coordinate of the centroid) of each component for which we just found the area. For all the circles, C_x is just the midpoint value, so:

A_{Cx} = 3.75

B_{Cx} = 5

C_{Cx} = 1.5

D_{Cx} = 2.53

E_{Cx} = 3.96

For the triangle **C_x**, we average the **x** coordinates of its vertices:

$$C_x = \frac{(V1_x + V2_x + V3_x)}{3}$$

F_{Cx} = (7.8 + 6.3 + 6.0) / 3 = 6.7

Cx of the fin is therefore (note that we are subtracting instead of adding):

$$C_x = \frac{\left(\left(A_{Cx} \times \frac{1}{2}Area(A)\right) - \left(B_{Cx} \times \frac{1}{2}Area(B)\right) - \left(C_{Cx} \times \frac{1}{2}Area(C)\right)\right)}{Total\ Fin\ Area} + \frac{-\left(D_{Cx} \times \frac{1}{2}Area(D)\right) - \left(E_{Cx} \times \frac{1}{2}Area(E)\right) - \left(F_{Cx} \times \frac{1}{2}Area(F)\right)}{Total\ Fin\ Area}$$

= ((3.75*22.1) - (5*9.82) - (1.5*.38) - (2.53*.28) - (3.96*.2) - (6.7*.6)) / 10.82

= ((82.88) - (49.1) - (.57) - (.71) - (.79) - (4.02)) / 10.82

= 2.56

The dashed purple line on the colored figure above shows the location of **C_x**. Now we can calculate **ε** using the formula we have seen before:

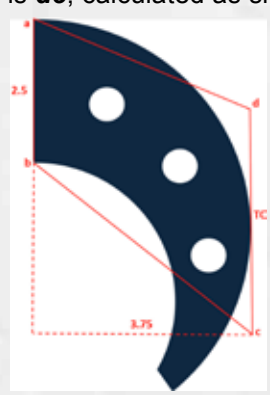
$$\varepsilon = \left(\frac{C_x}{RC}\right) - 0.25$$

(recalling that **ε** is a measure of distance expressed as a fraction of the whole root chord). **ε = 2.56/2.5 – 0.25 = 0.77**

Now let's calculate this fin's flutter velocity. Since we do not need sweep length (we have already calculated **C_x**), the only fin parameter we don't have at this point is the tip chord length. We could use the width of the end of the fin arc, which is the square root of the sum of the squares of the vertex coordinate differences:

$$\sqrt{((6.3 - 6)^2 + (2.75 - 2.29)^2)} = 0.55$$

However, the curved sweep of the fin to the rear suggests a different approach would be a better choice. As we did for elliptical fins, we will find a "pseudo" tip chord length of a trapezoidal fin that gives the same area as the bat wing fin. We do this by setting the value of the area of the bat wing fin equal to the area of a trapezoidal fin with the same root chord and semi-span length (height), and then solving for tip chord length. This process is depicted in the figure below. Trapezoid ***abcd*** has the same area as the bat wing, and the "pseudo" tip chord length is ***dc***, calculated as shown.



$$TC = dc = \left(\frac{Bat\ Wing\ Fin\ Area}{Height} \times 2\right) - Root\ Chord\ Length$$

TC = (((10.82 / 3.75) * 2) - 2.5) = 3.27. This is the value we will use to calculate **V_f**:

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By John K. Bennett

Now let's assume we are designing a rocket with bat wing fins of this shape whose dimension are in inches, and that we have chosen to use balsa fins that are 1/16" in thickness. For this exercise, assume that the launch altitude is 400 ft, launch temperature is 65 deg. F, and that the predicted height of our rocket at maximum velocity is 1000 ft. Summarizing the inputs to the fin flutter velocity calculator spreadsheet (overridden values shown in **red**):

The $\mathbf{V_f}$ result given these inputs is 85 ft/sec (about 58 mph). That's very low. If we double the balsa thickness (to 1/8"), $\mathbf{V_f}$ increases to 240 fps (163 mph). If we change the material to 1/16" birch aircraft plywood, $\mathbf{V_f}$ is 138 ft/sec (94 mph). Doubling the plywood thickness to 1/8" increases $\mathbf{V_f}$ to 392 ft/sec (267 mph). Small model rockets rarely exceed 250 mph, but larger and higher power rockets can approach or exceed Mach 1.

		Data to be Entered	Imperial Units	
Launch Site Data				
MaxV	=	maximum predicted rocket velocity	250	ft/sec
AMaxV	=	predicted altitude at predicted maximum rocket velocity	1000	ft
LSA	=	launch site altitude (ASL)	400	ft
TLS	=	temperature at launch site	65	deg F
Use Default Temp?	=	Use Default Sea-Level Temp (**DST**) or Launch Site Temp (**LST**)	DST	DST or LST
Fin Geometry Data				
t	=	fin thickness	0.0625	in
m	=	fin sweep length	Don't Care	in
TC	=	tip chord length	3.27	in
RC	=	root chord length	2.5	in
SSL	=	semi span length (height)	3.75	in
G_E (shear modulus)		Shear Modulus (doubled in calculation if tip-to-tip reinforcement)	33359	psi
T2T	=	Tip-to-Tip reinforcing present?	NO	YES or NO
		Calculated Values		
Cx (for trapezoidal fins) (edit formula for other fin shapes)		$C_x = \frac{(2 \times TC \times m) + TC^2 + (m \times RC) + (TC \times RC) + RC^2}{3(TC + RC)}$	2.56	in
t/c (thickness ratio)		**fin thickness / root chord length**	0.0250	
λ (lambda) (taper ratio) (create "pseudo" tip chord if nec.)		**tip chord length / root chord length**	1.3080	
Fin Area (trapezoidal fin) (edit formula for other fin shapes)		$Area = Height \times \frac{Tip\ Chord\ Length + Root\ Chord\ Length}{2}$	10.820	in sq
A (aspect ratio)		**(semi-span length or height)^2 / fin area**	1.2997	

Therefore, in order make the best choices for best fin material and thickness, we need to know how fast our rocket is expected to fly on the largest motor we intend to use. See the original article (PoF #615[1]) for a discussion of how we might make these choices.

OpenRocket and RockSim both support custom fin shapes, but to my knowledge, neither simulator considers fin holes to have aerodynamic significance (if fin holes are allowed at all). We can manually adjust fin weight in the simulator to account for the holes, but that's about it. Also, the aerodynamic effect of fin holes is unpredictable using simple analysis tools like those employed here. In general, unusual fin shapes may have unexpected flight results. Novel fin designs should be flown with caution, and only when it is safe to do so. Also, it is a good idea to alert the RSO when testing a new fin design for the first time.

In this article, we calculated the centroids using first principles, but a lot of helpful guidance can be found at Wikipedia's "List of Centroids".[5]

Custom fins are readily designed using tools like Fusion 360, which can export either DXF (for laser cutting) or STL (for 3D printing) files. A lot of guidance on this, material selection, and related subjects can be found online.

That concludes Part 1. In Part 2, we will show how to analyze arbitrary fin shapes using multi-sided polygon triangulation (and a bit of computer programming).

End Note

To reiterate what I said in PoF #615, these methods only estimate the fin flutter velocity. The choice of input values (altitudes, temperatures, fin dimensions, and in particular, fin material shear modulus) will have a significant impact on the results. We will always strive to use the best data available, but it is important to remember that the final result is only an estimate.

1 https://www.apogeerockets.com/education/downloads/Newsletter615.pdf

2 https://github.com/jkb-git/Fin-Flutter-Velocity-Calculator

3 https://www.apogeerockets.com/education/downloads/Newsletter488_Large.pdf

4 Polygon triangulation for an arbitrary polygon is an interesting problem in computational geometry. For our purposes, all we need to know is that the minimum number of triangles for an n-sided polygon is (n-2). And it really does not matter if we have an extra triangle or two when we partition our fin. We will revisit this issue later in the article.

5 https://en.wikipedia.org/wiki/List_of_centroids

About the Author

John Bennett is an engineering Professor Emeritus at the University of Colorado Boulder, and a TRA and NAR member in OregonRocketry. Using Brinley's book as a guide, he built and flew many Zn/S and KN03/sugar rockets as a teenager. In retirement, he is now rediscovering his love of amateur rocketry, this time with better supervision.

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Tim's Messy Desk

By Tim Van Milligan

NARCON 2024 is coming up later this month, and I've been getting ready for it this week. I'm doing a presentation on how to make ultra-lightweight rockets using two-part molds. It normally takes several hours to make a single rocket tube, so I had to do a lot of prep work ahead of time so that I can try to condense the presentation down to about 40 minutes long. I wanted it to be as "live" as possible, but because there is so much time mixing up epoxy and waiting for things to dry, I eventually decided to make it into a video.

That's what I've been doing this week. It is still too long, so much of the video will be run at 2X speed. It is kind of comical to watch at that speed, but I think most people will be able to get the gist of what I'm doing.

For the past few years, I've been doing a lot of building of composite rockets out of carbon-fiber and epoxy. I'm always so amazed at how strong and lightweight carbon fiber is. It is almost 5 times as stiff as fiberglass, and significantly lighter if you keep the amount of epoxy to a minimum. I used to make tubes from fiberglass cloth, but I just can't think of many advantages of "glass" over carbon fiber. In the end, just the ease of handling the carbon fiber was the final push I needed to completely abandon fiberglass for rocketry use. If you're going to use composites in rocketry, just use carbon fiber. There is no doubt in my mind about this.

So in this NARCON presentation, I'll be showing all my secrets that I've discovered over the last five years to make carbon fiber tubes in a 2-part mold. I first started making competition-style composite airframe tubes in late fall of 2019 after getting a lot of hints from Kevin Kuzek. But I had a lot of technical obstacles to overcome.

Figure 1: A finished carbon fiber rocket.

My goals were many: I wanted the rocket tubes to be super lightweight (under 3.7 grams), strong, aerodynamically smooth, and have compound curves. Additionally, they had to be reusable (had to withstand the intense heat of the ejection charge), and air tight, easy enough to assemble that my children could replicate it, and require no post-processing to repair. And finally, I wanted the construction process to be repeatable from one part to the next so that there weren't a lot of rejects and wasted effort. Usually, when you have a long list of goals, they'll tell you to just pick two, and compromise on the others. But I felt that if you can't have it all, then why bother.

With so many goals, there were a lot of challenges that I had to overcome. Things like: removing parts from the mold without breaking them, achieving a consistent surface finish, having them be strong enough to survive a launch, getting them to be air tight so the motor ejection charge could push out a parachute from them, getting the glass smooth surface that I wanted for low drag, and reducing the weight to a bare minimum. Each of these problems literally took months of trial and error to figure out a solution.

But overcoming the engineering challenges excited me. I get energy from working on multiple problems like this. So it didn't bother me to make mistakes, as long as I was learning. Unfortunately, I can be a slow learner.

Figure 2: A 3D printed mold with the carbon fiber laid into it.

I've found that success for this project takes a combination of solutions. Sometimes it was a chemical solution, like what mold release to use to get them out of the mold. Then it could be a "materials solution," like what kind of liner is needed to prevent the epoxy from sticking to the wrong place. Other times it was an "application solution," such as how do you apply the epoxy to the mold. Then there are "physics solutions," such as using capillary action to get the epoxy to spread to places you normally can't reach. Finally, there are a lot of tactical solutions that I had to come up with, which are the processes and sequence of steps that, if followed, will yield the greatest results in the shortest amount of time.

I put a lot of sweat into the process, and unfortunately repeated a lot of the same mistakes again and again. The biggest breakthroughs came about after I had finally started to journal my learnings in a notebook. It wasn't so much the process of recording the learnings from the failed experiments, which by itself was helpful. But just taking the time to write with a pen and paper gave my brain time to ponder the problems. Thinking time… That is what was the key ingredient to success. Often, while writing mid-sentence, an idea would come to me for a new experiment that might solve the problem I was working on. Those were the eureka moments that I enjoyed the most.

About two months ago, I finally tackled the last of the obstacles that kept me from reaching all of the goals I wanted to achieve. It was a happy day to get that nearly perfect tube from the mold, and I was very proud. In fact, on the weight goal of 3.7 grams, I actually exceeded that target by a significant amount, and I'm consistently producing tubes that weigh around 2.5 grams.

However, to be honest, there was a little bit of a let-down when I checked off that last problem because it meant that my brain didn't have another engineering problem to overcome. At this point, it is no longer a research and development project. Now it is just a "production" project of making the same airframe tubes over and over again. It just doesn't have the excitement that I get from learning something new.

Since I'm not excited about being a factory producer of carbon fiber tubes for competition rockets, I need to

Figure 3: Complex shapes can be made using 2-part molds

train other people to make them. And that is where this NARCON presentation comes in.

I've made a little preview teaser video that shows how the airframes are removed from the mold and trimmed to their final size. I'll post it on YouTube so that you can get a feel for what is possible from this process. You'll find it at: https://youtu.be/Bgwm6qdOJKM

Be sure to sign up for NARCON at: https://www.accelevents.com/e/vNARCON-2024. I'm sure you'll enjoy it. I know I always do because I get to learn so many new things about rocketry.

VIDEO: Making Composite Airframe Tubes for Model Rocketry

See also:

Making Carbon Fiber Nosecones with a 3D Printed Mold - https://www.apogeerockets.com/education/downloads/Newsletter581.pdf

How 3D Printing Allows Extreme Rocket Designs - https://www.apogeerockets.com/Peak-of-Flight/Newsletter554