9/9/2006 ™

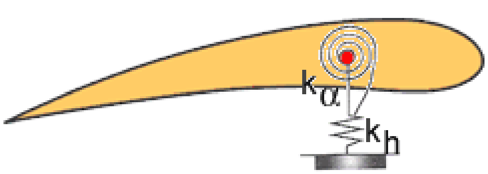
AeroFinSim 4.0

Fin Aeroelastic Analysis Software
Includes Spin Stabilization &
Unsteady Torsion-Flexure Flutter

Are Your Fins Strong Enough To Survive A Wild Flight?
If you don't know how strong your fins are, you'll either be launching an unsafe rocket, or one which is overbuilt or that won't travel as high as you'd like. Can you tell simply by looking? FinSim will predict how strong your fins are. More importantly, it tells you if they will stay attached to the rocket under the extreme loads of a wild flight. FinSim can also tell you if the fins are too sturdy, meaning they are heavier and thicker than they actually need to be. If so, rocket performance will suffer.

What is FinSim?
First, FinSim is a structural analysis program. This portion of the program determines how strong the fins are by determining the aerodynamic fin loads. You can't know if your fins are strong enough unless you know the aerodynamic forces acting on them during launch. In its structural analysis mode, FinSim looks at the material of the fins, how long the fins are, their span, how thick they are, the size of the fillets, how they are attached to the rocket (through-the-wall or butt-joint), and what type of glue is used. Using this information FinSim computes the maximum allowable bending force the fin can handle without causing fin separation. Then, using the maximum angle-of-attack the rocket will attain, FinSim quickly computes aerodynamic loading based on the geometry of the fins in terms of lift and drag. Then, the program displays the highest speed that can be tolerated before the fins will shred or separate from the rocket.

Second, FinSim is an aeroelasticity program that predicts flutter and divergence velocity for up to six sets of fins. Fin flutter and divergence are vibrations of the fin caused by the coupling of free flight aerodynamic forces with lightly damped structural modes of vibration, that can range from a slight buzzing sound to instances where the oscillations are so severe the fins are stripped off the rocket. In any case, fin flutter and divergence will create excess drag, causing the rocket to lose altitude and flight speed. FinSim will predict when flutter occurs, so you can either beef up the fins or choose a different rocket motor that limits the speed of the model. Please note that for flutter/divergence and fin stress analyses the user needs to manually enter only six fin-related variables to determine flutter velocity, divergence velocity and maximum allowable rocket velocity based on allowable material strength.



To determine flutter and divergence velocity, FinSim assumes each fin is mounted on bending and torsion springs located at the fin's elastic axis (Xea) and the aerodynamic center is located at the 1/4 chord point for subsonic flight. A critical velocity will cause either a static instability (torsional divergence) or an oscillatory instability (flutter). FinSim computes divergence velocity and flutter velocity for up to 6 fin sets.

Third, the SpinSim routine determines stability (Xcp) of spin stabilized rockets that use canted fins.

FIRST, SOME CONCEPTS ABOUT AEROELASTICITY

DIVERGENCE VELOCITY: Fin or wing divergence is an example of a steady-state aeroelastic instability. If a wing in steady flight is accidentally deformed an aerodynamic moment will generally be induced which tends to twist the fin/wing. Fin/wing twisting is resisted by the restoring elastic moment along the elastic axis (ea). However, since the elastic stiffness is independent of the flight speed, whereas the aerodynamic moment is proportional to the square of the flight speed, there may exist a critical speed, at which the elastic stiffness is barely sufficient to hold the fin in the disturbed position. Above such a critical speed, an accidental deformation of the fin/wing will lead to a large angle of twist (torsion). This critical speed is called the divergence speed, and the fin/wing is said to be torsionally divergent. Rocket fins should be designed so the divergence speed is never exceeded at any altitude during the flight.

$$q_D = \frac{K_\alpha}{Se\,\dfrac{\partial C_L}{\partial \alpha}}$$

Where, q_D = Divergence velocity, K_α = Torsion spring stiffness
S = Fin surface area, $e = X_{ea} - X_{ac}$, $\partial C_L/\partial\alpha$ = Fin lift slope = CL_α (2π for 2-D fins)

FLUTTER VELOCITY: Flutter is a dynamic instability of an elastic body (wing or fin) in an airstream and like divergence the only forces necessary to produce flutter are those due to the deflection of an elastic structure from its initially un-deformed state. The flutter velocity or critical speed $\mathbf{U_F}$ and frequency ω_F are defined respectively as the lowest airspeed and corresponding circular frequency at which an elastic body flying at a given atmospheric pressure and temperature will exhibit sustained harmonic oscillation. When there is no flow and the rocket's fin is disturbed, say, by a poke with a rod, oscillation or vibration occurs, which is damped (reduction of amplitude caused by structural resistance) gradually over successive vibration cycles. When the speed of flow is gradually increased, the rate of damping of the oscillation of the disturbed fin increases at first. With further increase in rocket velocity, however, a point is reached at which the damping rapidly decreases. At the critical flutter velocity, an oscillation can just maintain itself with steady amplitude. At speeds above this critical condition (UF), any small accidental disturbance of the fin from a gust of wind can serve as a trigger to initiate an oscillation of great violence that will rip the fin right off the rocket causing an unstable flight condition. Rocket fins should be designed so the flutter velocity and divergence velocity is never exceeded. Please note that no flutter velocity exists for center of gravity positions (Xcg) forward of the elastic axis (Xea) of the fin or wing. Please note the two equations presented here are an approximation based on steady state aerodynamic assumptions and are only valid for $\omega_\alpha/\omega_h > 1$ and mass ratio (μ) < 10. Where, ω_α/ω_h is the ratio of the natural torsion frequency to the natural bending frequency. For a more precise analyses of the critical flutter velocity and divergence velocity use either the Theodorsen method or U-g method located on the Torsion-Flexure (2-D) Unsteady Flutter screen.

$$\frac{U}{b\omega_\alpha} = \sqrt{\left(\frac{2m}{\rho_\infty bS}\right)\frac{{r_\alpha}^2}{\dfrac{\partial C_L}{\partial\alpha}\left[x_\alpha + \dfrac{e}{b}\right]}}$$

Where, U = Flutter velocity, ω_α = Uncoupled torsion frequency, b = Average fin half-chord, m = Fin mass, S = Fin surface area, r_α = Fin radius of gyration
$e = X_{ea} - X_{ac}$, $x_\alpha = X_{cg} - X_{ea}$,
$\partial C_L/\partial\alpha$ = Fin lift slope = CL_α (2π for 2-D fins)

Note: These equations are a quasi-steady aerodynamics approximation (Pines' approximation) for subsonic flutter and divergence. These equations are based on quasi-steady aerodynamic theory for low speed flight.

TORSION-FLEXURE (2-D) UNSTEADY FLUTTER ANALYSIS

The discussion in the previous section of the Pines' flutter velocity approximation is based on quasi-steady aerodynamic assumptions. Therefore, as stated in *An Introduction to the Theory of Elasticity*, the Pines' approximation is a practical tool for determining flutter velocity of low speed aircraft and model rockets. However, high speed aircraft and model rockets (Mach < 1) require the linearized aerodynamic theory as represented by Theodoren's function, **F(k) + i G(k)** and implemented on the new **Torsion-Flexure (2-D) Unsteady Flutter** analysis screen. Simply stated, the aerodynamic forces of the linearized theory are coupled with the assumption of a two-dimensional standard airfoil, that is an airfoil having two degrees of freedom: a bending or flexure degree of freedom, h measured around the elastic axis and a pitching or torsion degree of freedom, α measured around the elastic axis of the airfoil.

INPUT VARIABLES FOR TORSION-FLEXURE (2-D) UNSTEADY FLUTTER

g = Structural damping coefficient, usually a value between 0.005 and 0.05 for metallic structures

μ = mass ratio = $m/(\pi\ \rho\ b^2)$ = $(4/\pi)\ (\rho_m/\rho_{air})$ (t/c) = Ratio of the mass of the wing to the mass of a cylinder of air of a diameter equal to the chord of the wing.

a_h = Axis of rotation (elastic axis) location from the wing/fin center-chord = 2 Xea - 1

x_α = C.G. location aft of the axis of rotation (a_h) location = (2 Xcg - 1) - a_h

r_α = Radius of gyration about the elastic axis = SQR[I_α / (m b^2)]

ω_α = Natural angular frequency of torsional vibration around 'a' in vacuum (rad/sec)

ω_h = Natural angular frequency of wing in flexure (bending) in vacuum (rad/sec)

b = Half chord, used as reference unit length (inches)

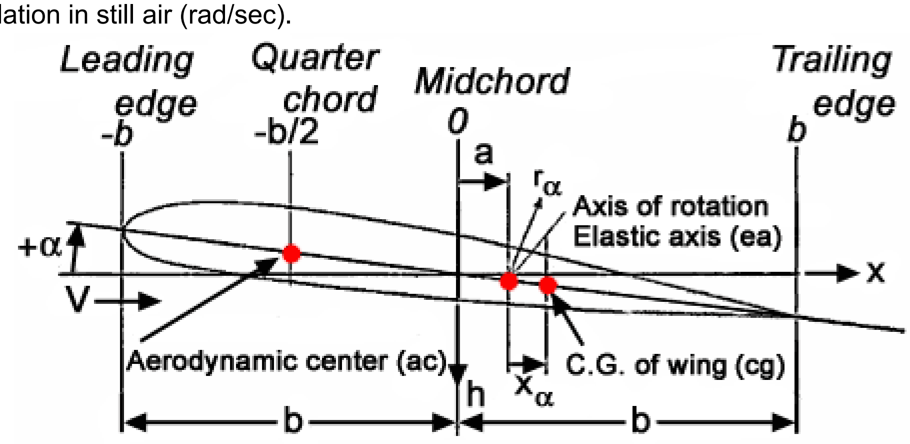
Where:

Xcg = Center of gravity location measured from the airfoil leading edge divided by the chord length (c).

Xea = Elastic axis location measured from the airfoil leading edge divided by the chord length (c).

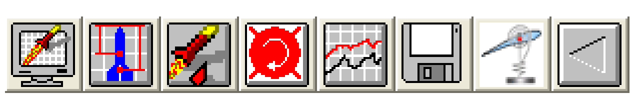
and r_α (radius of gyration) is made non-dimensional by dividing by b (half chord), c = chord length and t = thickness.

k = ω_α b / U = Reduced frequency or Strouhal number represents the ratio of the characteristic length of the body (b) to the wave length of the disturbance. Where U is the mean speed of the flow and ω_α is the fundamental frequency of the wing in torsional oscillation in still air (rad/sec).



The Standard 2-D Wing Section

Please Note: Click the  icon located on the main FinSim Flutter screen to access the new ***Torsion-Flexure (2-D) Unsteady Flutter*** analysis screen for modeling unsteady torsion-flexure wing oscillations using the Theodorsen method or U-g method to determine flutter and divergence velocity.



ToolBar located on the main screen

FINSIM FEATURES

1) Determine fin flutter critical velocity (UF) and fin divergence critical velocity (UD) using the Pines' approximate method.

2) Define aerodynamic loads using either the 3-dimensional Barrowman lift-slope (CN_alpha) or the 2-dimensional lift slope (CN_alpha).

3) Define up to six fin-sets using only five variables to define fin geometry.

4) Easily define rocket angle of attack, flight altitude, fin fillet radius and butt-joint or thru-the-wall fin mounts using simple options buttons.

5) Specify from a list of 25 common materials or manually enter modulus of elasticity, material density, poissons ratio and bending yield strength.

6) Specify from a list of 12 common adhesives or manually enter the adhesive allowable strength.

7) Fin allowable and adhesive allowable is displayed for comparison purposes.

8) Plot fin stress verses rocket velocity and see the maximum allowable velocity as limited by either the fin material or

9) Plot each fin set by simply clicking one of up to 6 fin-set option buttons.

10) By clicking **SHOW** or **HIDE** in the **Additional Results** menu in the toolbar, display Stress Concentration Factor due to fillets, Torsional Frequency, Bending Frequency, Fin-Tip Deflection and Maximum Fin Bending Moment.

11) Determine the stability margin (XCp-XCG) of spin stabilized rockets using canted fins to achieve rotational velocity.

12) FinSim instructions and SpinSim instructions are included with purchase and are accessible from within the program's HELP routine.

13) Specify a title on the main screen to differentiate between the various input data files. NOTE: Fin flutter and stress analysis files have the .FIN specification

14) Use the Classical 2-D Lift Slope, Barrowman 3-D Lift Slope or the new Supersonic Airfoil Lift Slope to define fin loads for flutter and stress analyses.

15) Location of the aerodynamic center (A.C.) automatically changes to the 25% chord length position for subsonic airfoils (Classical 2-D Lift Slope and Barrowman 3-D Lift Slope) and automatically changes to the 50% chord length position for supersonic airfoils (Supersonic Airfoil Lift Slope). Mach number is inserted or modified in the STRESS routine.

NEW FINSIM 4.0 FEATURES

16) Added the ability to model unsteady torsion-flexure wing oscillations using the **Theodorsen method** and **U-g method** to determine critical flutter velocity and divergence velocity. Also, included six test cases with reference pages.

17) Manually enter experimentally derived aeroelastic data on the **Theodorsen** and **U-g method** screen.

18) Increased the altitude corresponding to atmospheric density and pressure from 10K feet to 50K feet greatly increasing the atmospheric affect on flutter and divergence velocity.

19) In the **Additional Results** section on the main screen added output of material properties including Modulus of elasticity (E), Shear modulus (G), Poissons ratio, and Material density (ρ) in addition to the uncoupled bending frequency (ω_h) and torsion frequency (ω_α) of fin/wing vibration.

20) Improved accuracy of the Pines' approximate method for determining critical flutter and divergence velocity on the main Flutter analysis screen.

21) Fixed a few errors in the material properties data base, specifically the Polystyrene material.

22) Save 1/k, F(k), G(k), X1r(k), X2r(k), X1i(k), X2i(k) for the **SQR(X) verses 1/k** analysis to a CSV file. Also, Save k, F(k), G(k), U_F(k), g(k) for the **U verses g** analysis to a CSV file for later use in Excel or other spreadsheet programs.

(1) FLUTTER VELOCITY FOR THE 2ND STAGE FINS OF THE QUANTUM LEAP

The following FinSim analysis predicts flutter and divergence velocity for the second stage fins of the **PML Quantum Leap**. This FinSim unsteady Torsion-Flexure flutter analysis indicates the Quantum Leaps' **second** stage fins will flutter at approximately **0.76 Mach** (see Figure-4) and become fully divergent at **0.96 Mach**. In-flight video seems to indicate the **second** stage fins of the Quantum Leap will flutter at **0.90 Mach** when fiber-glassed. The FinSim critical flutter velocity result of **0.76 Mach** defines the earliest possible onset of flutter when the oscillations can just maintain themselves at small steady amplitude while the divergence velocity of **0.96 Mach** completely bounds the observed result. Above the critical flutter velocity any accidental disturbance can initiate oscillations of great amplitude. Therefore, the large oscillations observed at 0.90 Mach were probably triggered by an accidental disturbance of the airflow (gust of wind?) after exceeding the critical flutter velocity, explaining why the oscillations were observed at 0.90 Mach although flutter may have been occurring earlier in the flight as predicted by FinSim's result.

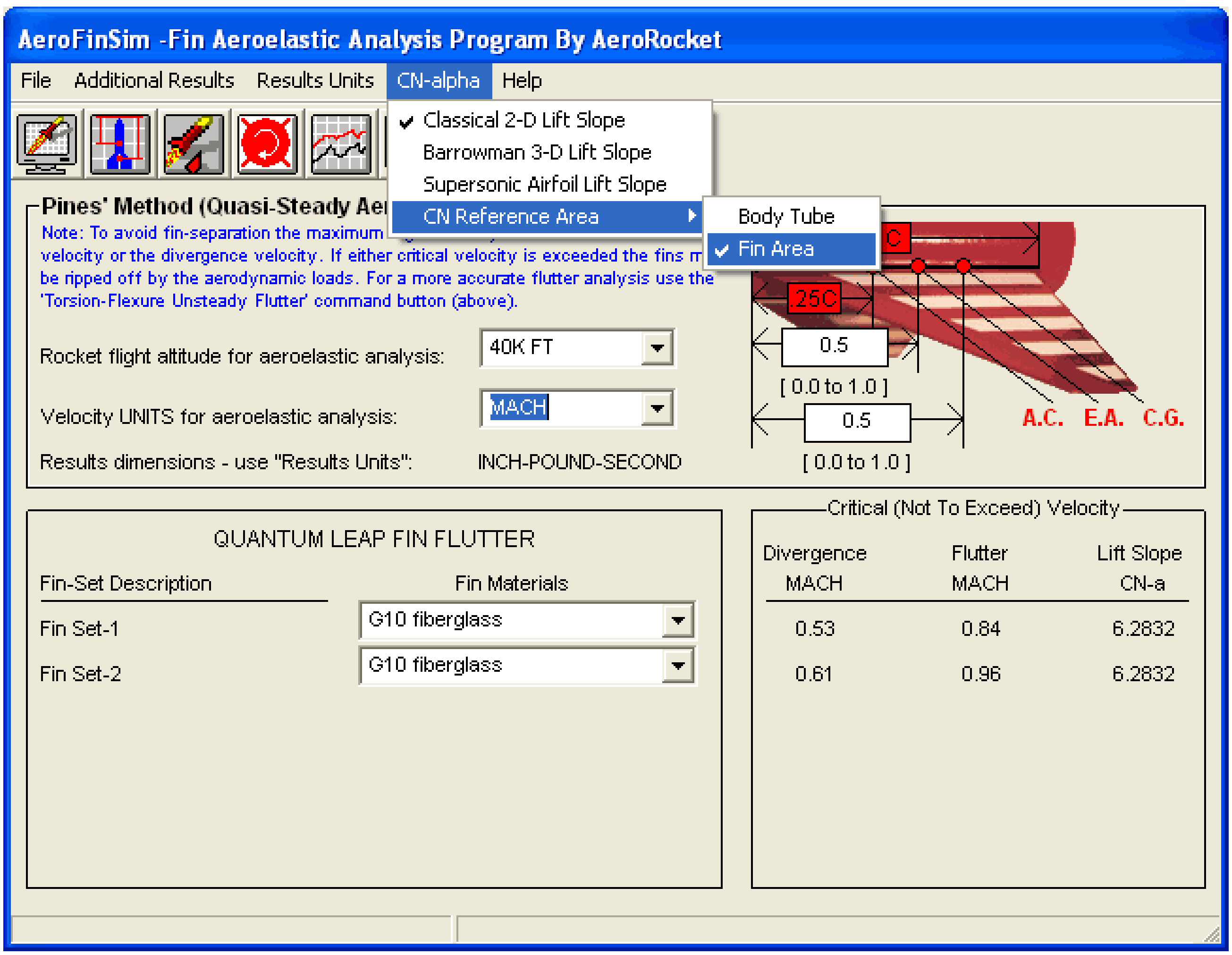


Figure-1: Main FinSim analysis screen displaying the Pines' approximate flutter results

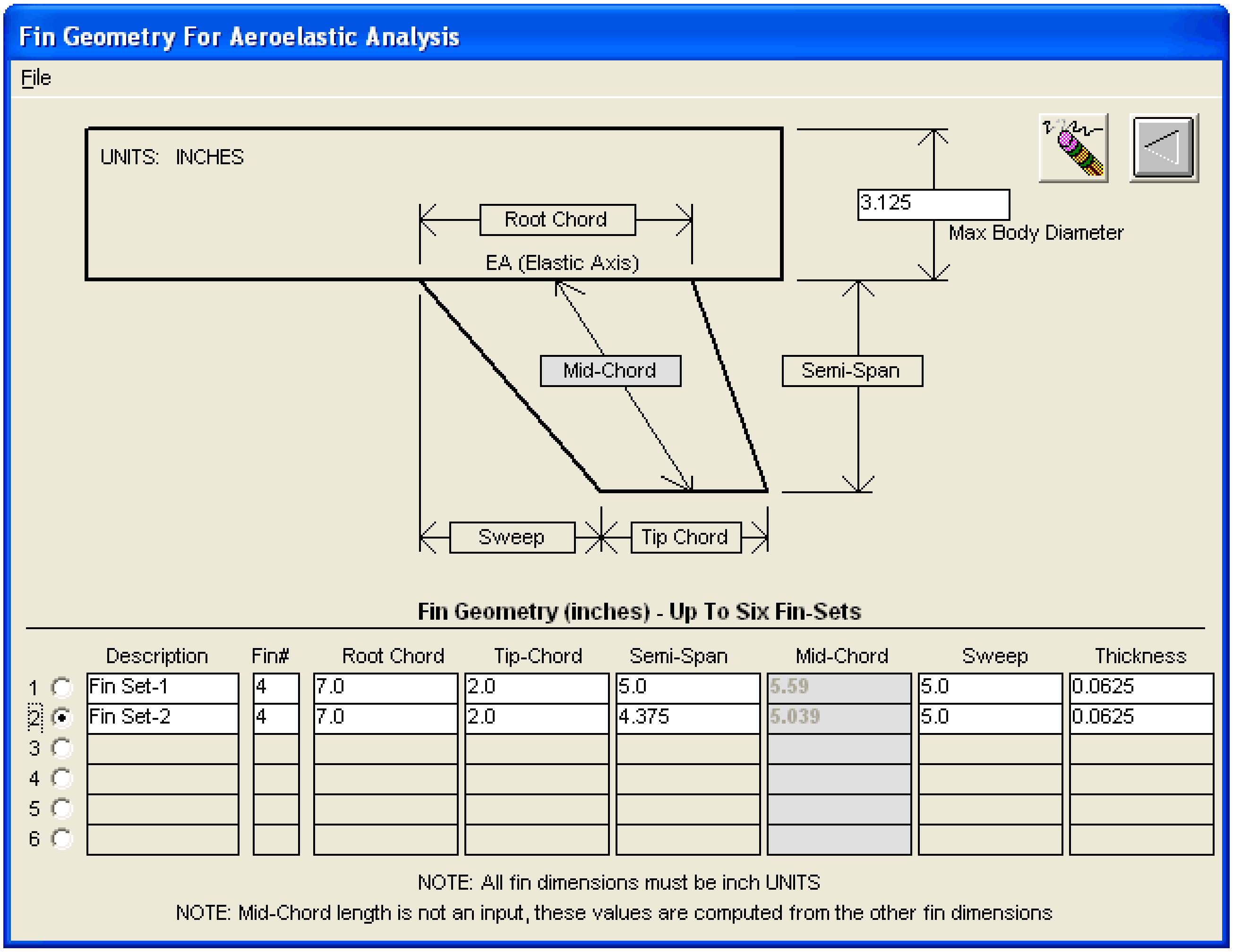


Figure-2: FinSim Input geometry screen

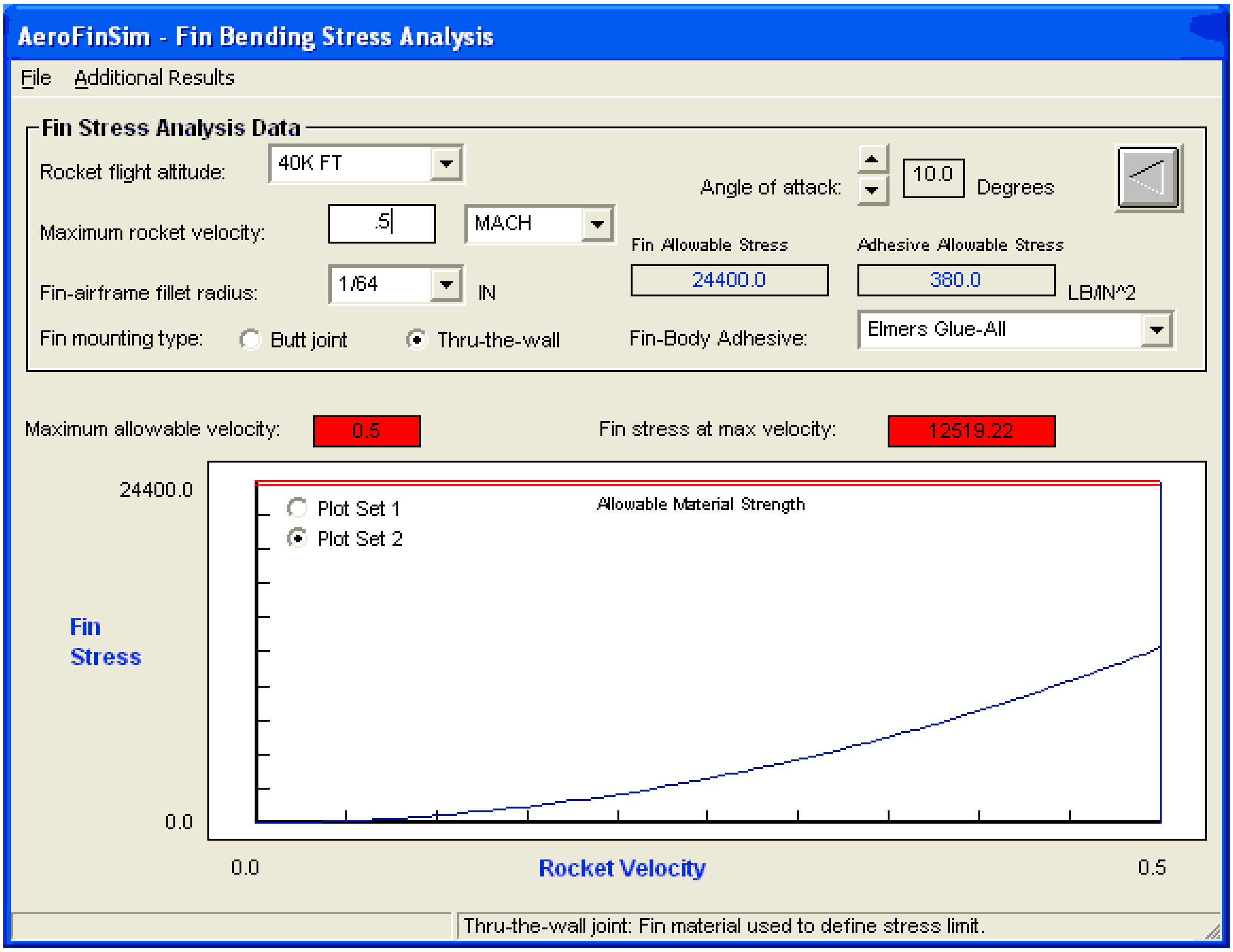


Figure-3: FinSim fin stress analysis screen

Click this icon  located on the main FinSim Flutter screen to access the new **Torsion-Flexure (2-D) Unsteady Flutter** analysis

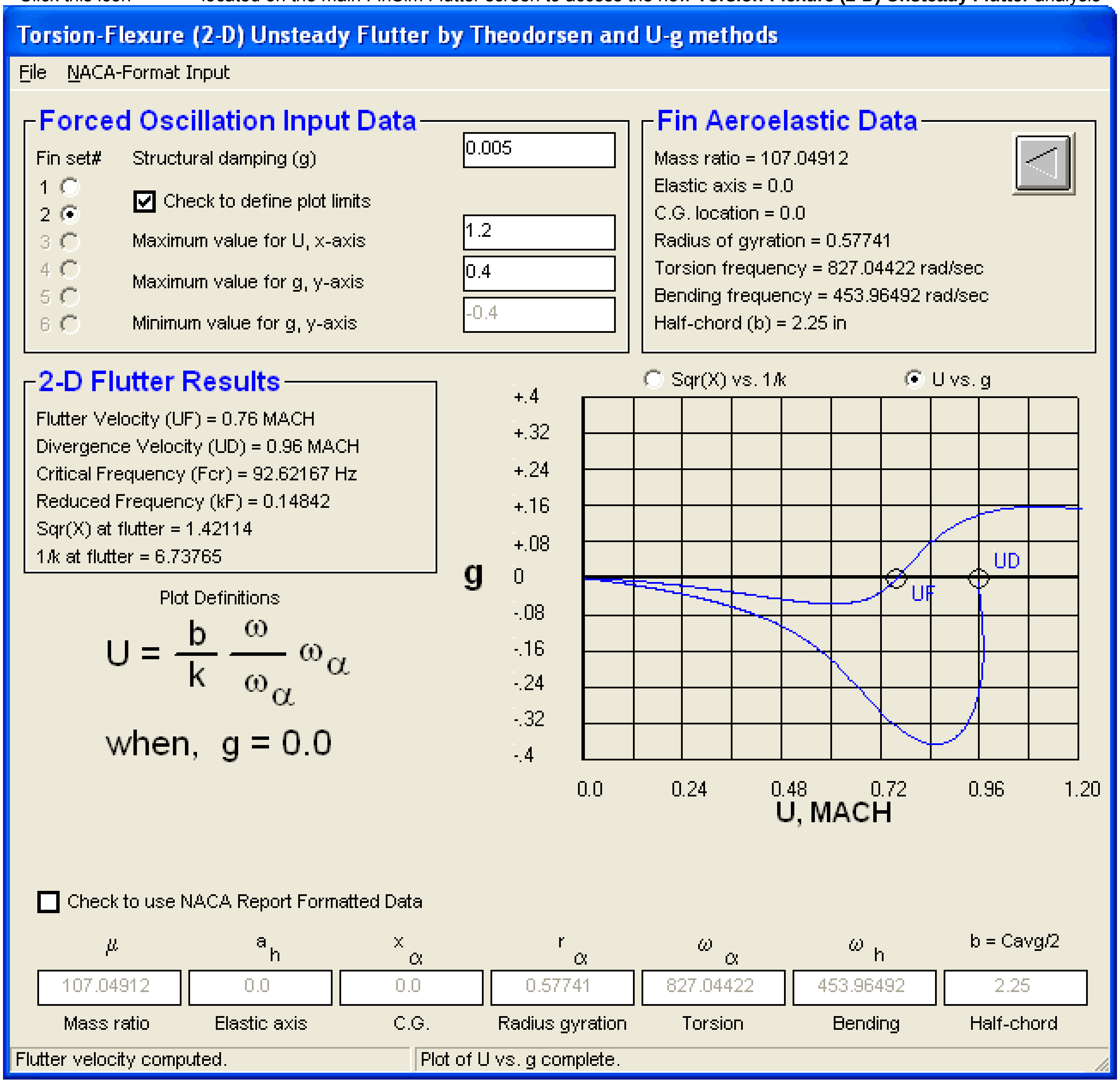


Figure-4: Flutter and divergence velocity using the U-g method

(2) FLUTTER VELOCITY COMPARISON WITH MSC/NASTRAN SOLUTION

The following is an unsteady Torsion-Flexure flutter validation of an airfoil mounted on bending and torsion springs located aft of the aerodynamic center of a fin or wing. A critical velocity will be found that will cause either a static instability (torsion divergence) or an oscillatory instability (flutter). Both divergence and flutter speeds of the airfoil are determined and compared to exact theory and a separate MSC/NASTRAN finite element analysis (FEA) technique using the K-method based on the exact Theodorsen function. The following table illustrates the usefulness of FinSim for accurately determining critical flutter and divergence velocity of typical cruciform model rocket fins. This example uses the **Theodorsen** and **U-g methods** to predict flutter and divergence velocity as described in NACA Report 685, Mechanism of Flutter by Theodorsen and Garrick on page 542 of the report. Comparison between FinSim results and the paper's results are excellent.

Fin Aeroelastic Data

g (structural damping) = 0.0
μ (mass ratio) = 20.0
a (elastic axis location) = -0.2
$\mathbf{x}_\alpha$ (c.g. location) = 0.1
$\mathbf{r}_\alpha$ (radius of gyration) = 0.5
ω_α (torsion frequency, rad/sec) = 25
$\omega_\mathbf{h}$ (bending frequency, rad/sec) = 10
b (half chord, inches) = 36.0

TORSION-FLEXURE AIRFOIL FLUTTER AND DIVERGENCE VELOCITY VALIDATION

Results	**Flutter Velocity**	**Difference**	**Divergence**	**Difference**
Exact Theory	169 ft/sec	**-**	216 ft/sec	**-**
MSC/NASTRAN	166 ft/sec	-1.8%	216 ft/sec	+ 0.0%
FinSim 4.0	**166 ft/sec**	-1.8%	**217 ft/sec**	+ 0.5%

Click this icon  located on the main FinSim Flutter screen to access the new **Torsion-Flexure (2-D) Unsteady Flutter** analysis

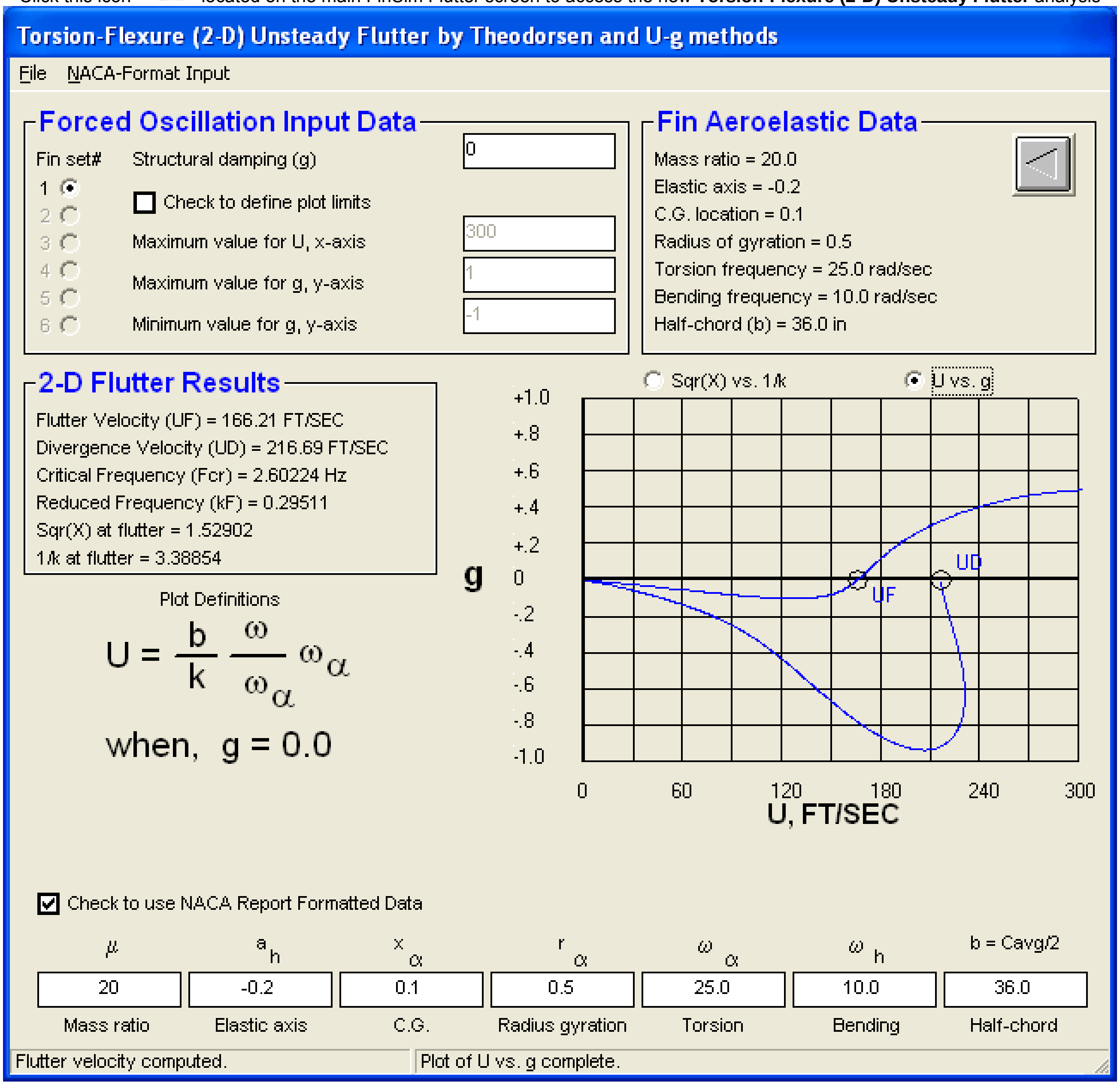


Figure-5: Flutter and divergence velocity using the U-g method

Click this icon  located on the main FinSim Flutter screen to access the new **Torsion-Flexure (2-D) Unsteady Flutter** analysis

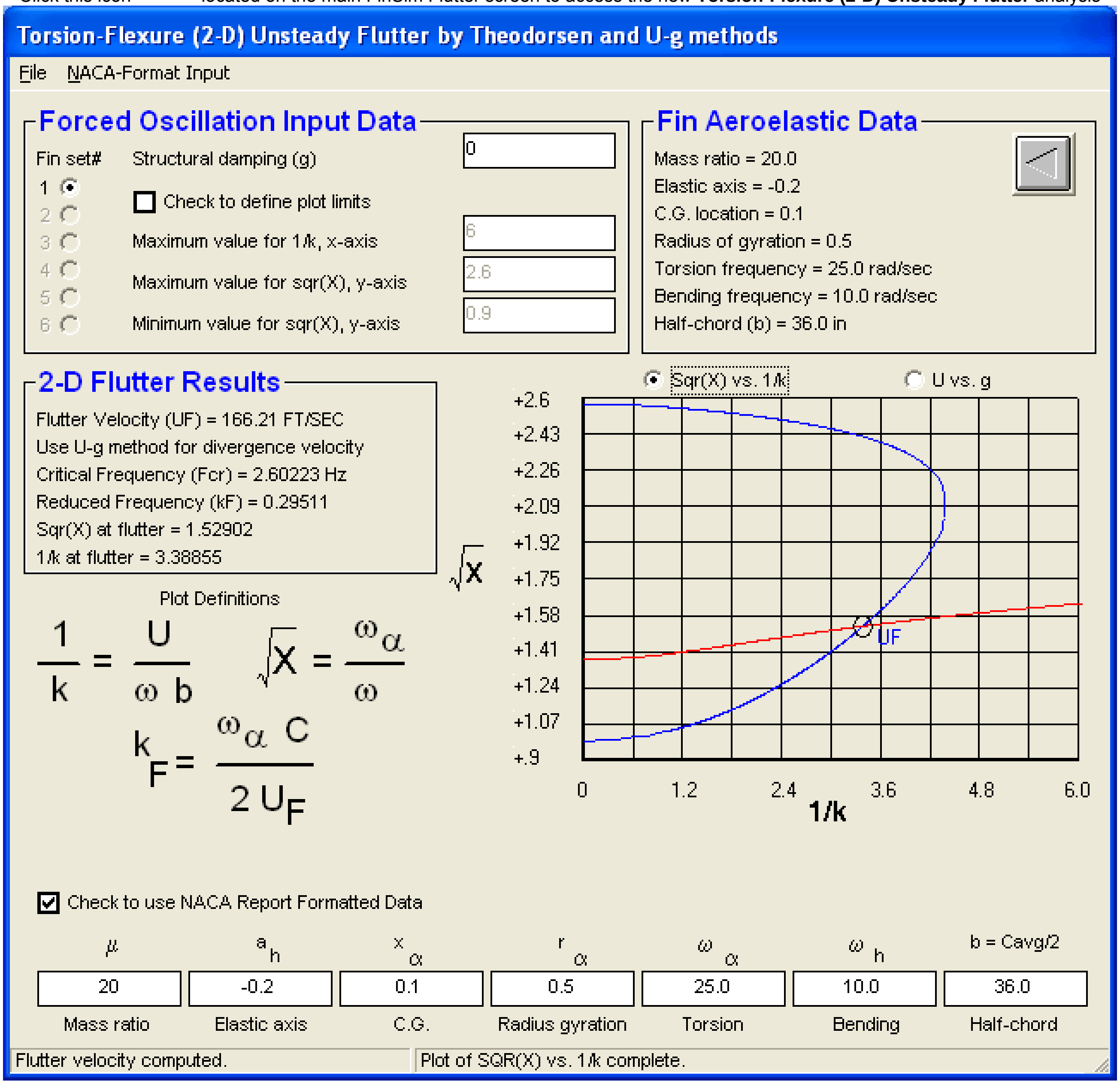


Figure-6: Flutter velocity using the Theodorsen method (SQR(X) verses 1/k)

(3) FLUTTER VELOCITY OF A WING FOR A LARGE MODERN AIRPLANE

This example uses the **U-g method** to predict critical flutter velocity for a wing described in NACA Report 685 as being for a large modern airplane. Please reference, NACA Report 685 Mechanism of Flutter by Theodorsen and Garrick on page 108 of the report. The parameters supplied by the report are as follows. Comparison between FinSim results and the reports results are excellent.

Fin Aeroelastic Data

g (structural damping) = 0.0
μ (mass ratio) = 4.0
a (elastic axis location) = -0.4
x_α (c.g. location) = 0.2
r_α (radius of gyration) = 0.5
ω_α (torsion frequency, rad/sec) = 90
ω_h (bending frequency, rad/sec) = 22.5
b (half chord, inches) = 72.0

UNSTEADY TORSION-FLEXURE FLUTTER VALIDATION

Results	Flutter Velocity	Difference	SQR(X)	Difference	1/k	Difference
NACA	567.0 mph	-	1.594	-	2.46	-
FinSim	**568.65 mph**	+0.29%	**1.592**	-0.125%	**2.46**	0.0%

Click this icon  located on the main FinSim Flutter screen to access the new **Torsion-Flexure (2-D) Unsteady Flutter** analysis

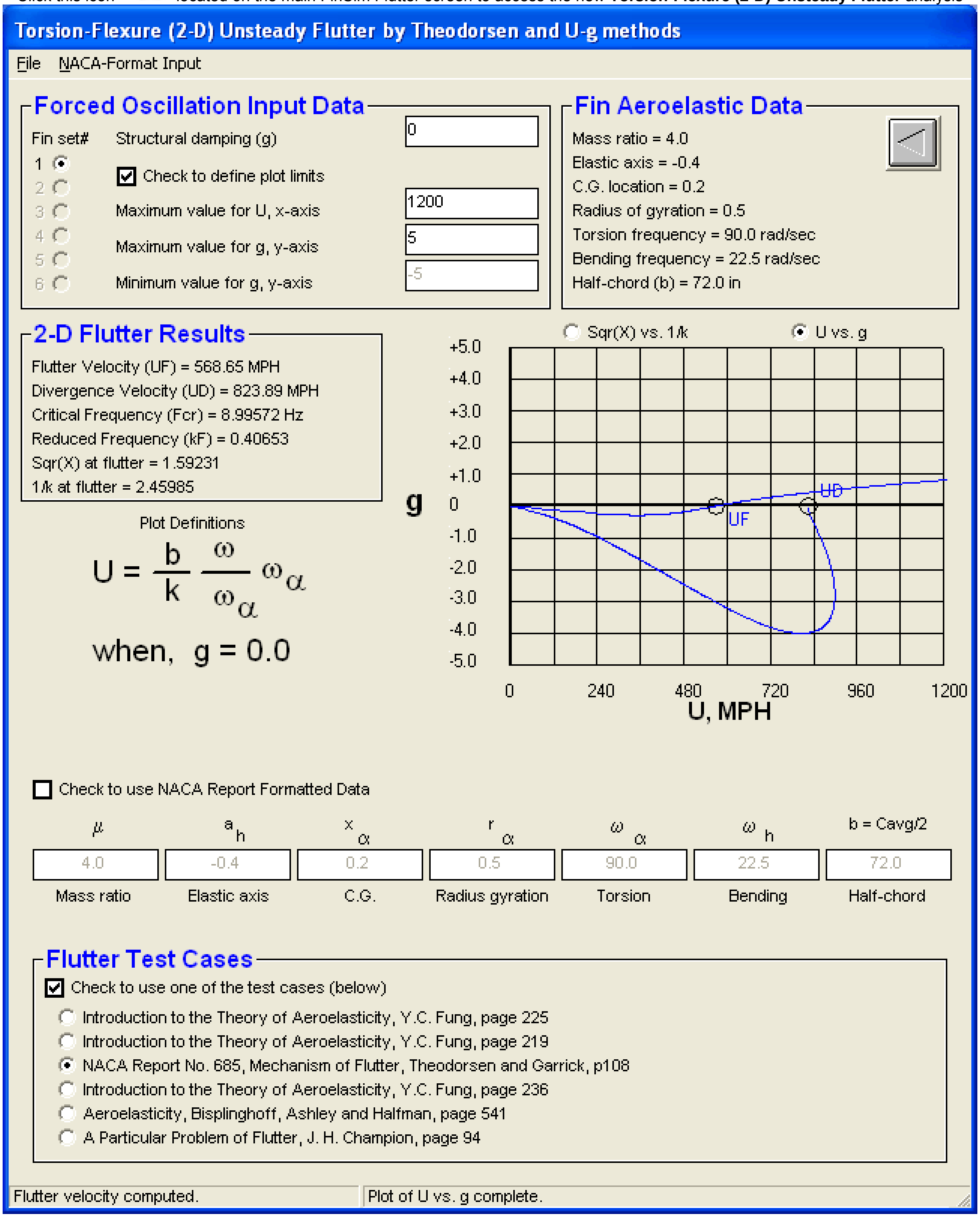


Figure-7: Flutter and divergence velocity using the U-g method

FIN STRESS ANALYSIS

The Fin Bending Stress Analysis computes maximum bending stress at the base of a fin with fillets. Thru-the-wall and Butt-joint fins are analyzed. The allowable stress is based either on the adhesive or the fin material allowable strength and depends on the fin-mount boundary conditions. Please consult any standard reference on strength of materials for more description of the equations listed below.

$$q = \frac{1}{2} \cdot \rho_{air} \cdot U^2 \qquad W = CL_{\alpha} \cdot \alpha \cdot q \cdot S$$

$$w = \frac{W}{L} \qquad M_{max} = \frac{w \cdot L^2}{2}$$

$$\sigma = \frac{M_{max} \cdot c}{Ixx} \qquad c = \frac{t}{2}$$

The following definitions apply for a fin analyzed as a uniform-load cantilever beam.

U = Flight speed of vehicle.
L = Average fin chord length.
α = Fin angle of attack (radians).
S = Surface area of fin.
q = Dynamic pressure acting on fin.
W = Total load at fin center of pressure location.
w = Fin loading per unit length of fin.
M_{max} = Moment at base of fin for a cantilever beam with uniform loading.
CL_{α} = Fin lift slope = $\partial CL/\partial\alpha$ = (2π for 2-D fins)
ρ_{air} = Flight air density.
σ = Maximum normal stress acting on outer fibers of fin.
c = Location to outer fiber of fin from neutral axis of fin cross-section.
t = Average fin thickness.

STANDARD MATERIALS	E_x (psi)	ρ (lb/in^3)	ν	S_{allow} (psi)
Aluminum	10000000	0.098	0.33	36000
Steel	30000000	0.286	0.29	60000
Balsa	415000	0.00506	0.35	1000
Basswood	1460000	0.0134	0.35	5900
Spruce	1600000	0.016	0.35	6700
Aircraft plywood (Birch)	2020000	0.0224	0.35	10100
Fir (Douglas)	1990000	0.02	0.35	8090
G10 fiberglass	3200000	0.066	0.35	24400
Cardboard	2000000	0.0434	0.35	10100
Paper	2000000	0.0434	0.35	10100
1/8 Aircraft Plywood	2020000	0.0224	0.35	10100
1/4 Aircraft Plywood	2020000	0.0224	0.35	10100
COMPOSITE MATERIALS	**E_x (psi)**	**ρ (lb/in^3)**	**ν**	**S_{allow} (psi)**
CFRP T300 N5208	10110000	0.058	0.30	217600
BFRP B(4) N5505	11390000	0.072	0.32	182700
CFRP AS H3501	7954000	0.058	0.28	209900
GFRP E-GLASS EPOXY	2750000	0.065	0.27	154000
KFRP KEV-49 EPOXY	4209000	0.053	0.32	203100
CFRTP AS-4 PEEK	7514000	0.058	0.30	308900
CFRP IM6 EPOXY	11360000	0.058	0.30	507600
CFRP T300 FBRT-934 4-MILL	8157000	0.054	0.32	190600
CCRP T300 FBRT-934 13-MILL	7639000	0.054	0.32	65120
CCRP T300 FBRT-934 7-MILL	6827000	0.054	0.32	53390
EPOXY	500500	0.043	0.35	1000
Kevlar	3300000	0.052	0.35	24400
Polystyrene PS	400000	0.038	0.33	7830
ADHESIVE MATERIALS	**E_x (psi)**	**ρ (lb/in^3)**	**ν**	**S_{allow} (psi)**
West System 105/205	461000	0.043	0.35	7846
West System 105/206	450000	0.043	0.35	7320
West System 105/207	514000	0.042	0.35	7509
West System 105/209	428000	0.042	0.35	7338
Aeropoxy PR2032/PH3630	2770000	0.042	0.35	45350
Aeropoxy PR2032/PH3660	2560000	0.041	0.35	45170
Aeropoxy PR2032/PH3665	3050000	0.041	0.35	45870
Bob Smith Grip-It	461000	0.04	0.35	2800
Bob Smith Royal Onyx	461000	0.04	0.35	3200
Elmers Glue-All	500500	0.039	0.35	380

ESTIMATING COMPOSITE MATERIAL PROPERTIES

FinSim has a built-in selection of representative materials that cover a broad spectrum of material types. However, occasionally the user may need to determine material properties based on the specific requirements of the fiber and matrix materials actually used for the fin material. In this case the **Rule of Mixtures** is used to estimate composite material properties as a function of the fiber and matrix constituents and their volume fractions. Using the **Rule of Mixtures** the relationship for the longitudinal modulus of elasticity (E_x) is the following:

$$\mathbf{E_x = f\ E_f + (1\text{-}f)\ E_m}$$

Which says that the longitudinal modulus of elasticity (E_x) is proportional to the volume fraction of the fiber material (f) and the volume fraction of the matrix material (1-f).

The other properties of the composite material such as density, poissons ratio and allowable stress are estimated in a similar way.

Composite material density

$$\rho = f\ \rho_f + (1\text{-}f)\ \rho_m$$

Composite material poissons ratio

$$\nu = f\ \nu_f + (1\text{-}f)\ \nu_m$$

Composite material allowable stress

$$S = f\ S_f + (1\text{-}f)\ S_m$$

FIN STABILIZATION ANALYSIS (SPINSIM)

In addition to flutter and fin stress analyses, FinSim has the ability to determine the stability of spin stabilized model rockets that use canted fins to achieve rotation. FinSim computes the center of pressure location of a spin stabilized rocket by applying the principals of gyroscopic motion. In addition, the SpinSim routine computes precession angle, added moment coefficient due to spin stabilization, total pitch moment coefficient with spin stabilization, rotary speed, precession speed and total drag coefficient (Cd) due to spin stabilization. The SpinSim routine requires information from either **mass properties CSV** export files or from manually entered inputs. Both the FinSim Manual and the SpinSim Manual are included during installation and are accessible from within the program's HELP routine. Please note that for a spin-stabilized rocket the center of pressure location (XCp) should be at least one body diameter <u>behind</u> the center of gravity (CG). This very same stability criterion is used to define the static stability of all fin-stabilized rockets and is referred to as the static margin (XCp-Xcg).

SpinSim uses fins, fixed at a constant angle of inclination, to induce rotation during flight. Spin stabilization is achieved when external aerodynamic forces change the rocket's angular momentum, L in time dt by an amount, dL. During this time interval the aerodynamic forces applied at the center of pressure (Cp), exert a restoring torque given as M = dL/dt around the center of gravity. The incremental moment caused by the restoring torque moves the effective Cp aft by an amount determined by the separation of the Cg and Cp and the value of the incremental moment. For more information about the technical aspects of spin stabilization and a step-by-step procedure please read the Spin Stabilization pdf instructions.

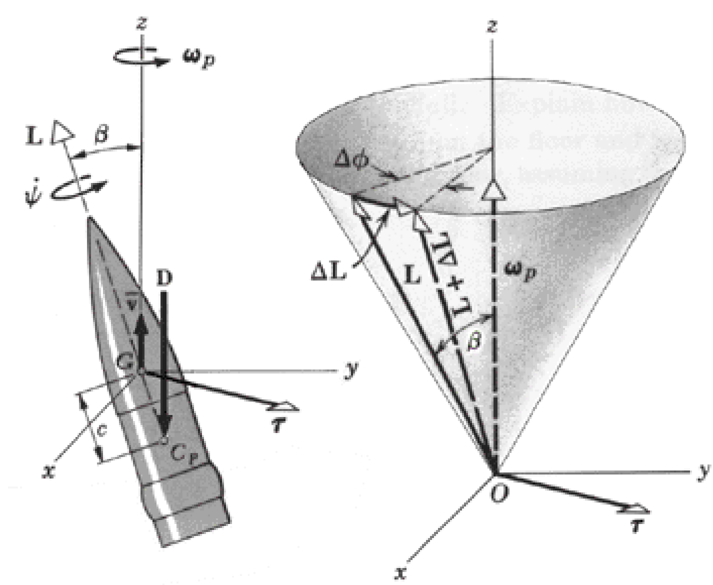


Figure-8: Basic definitions of Spin Stabilization

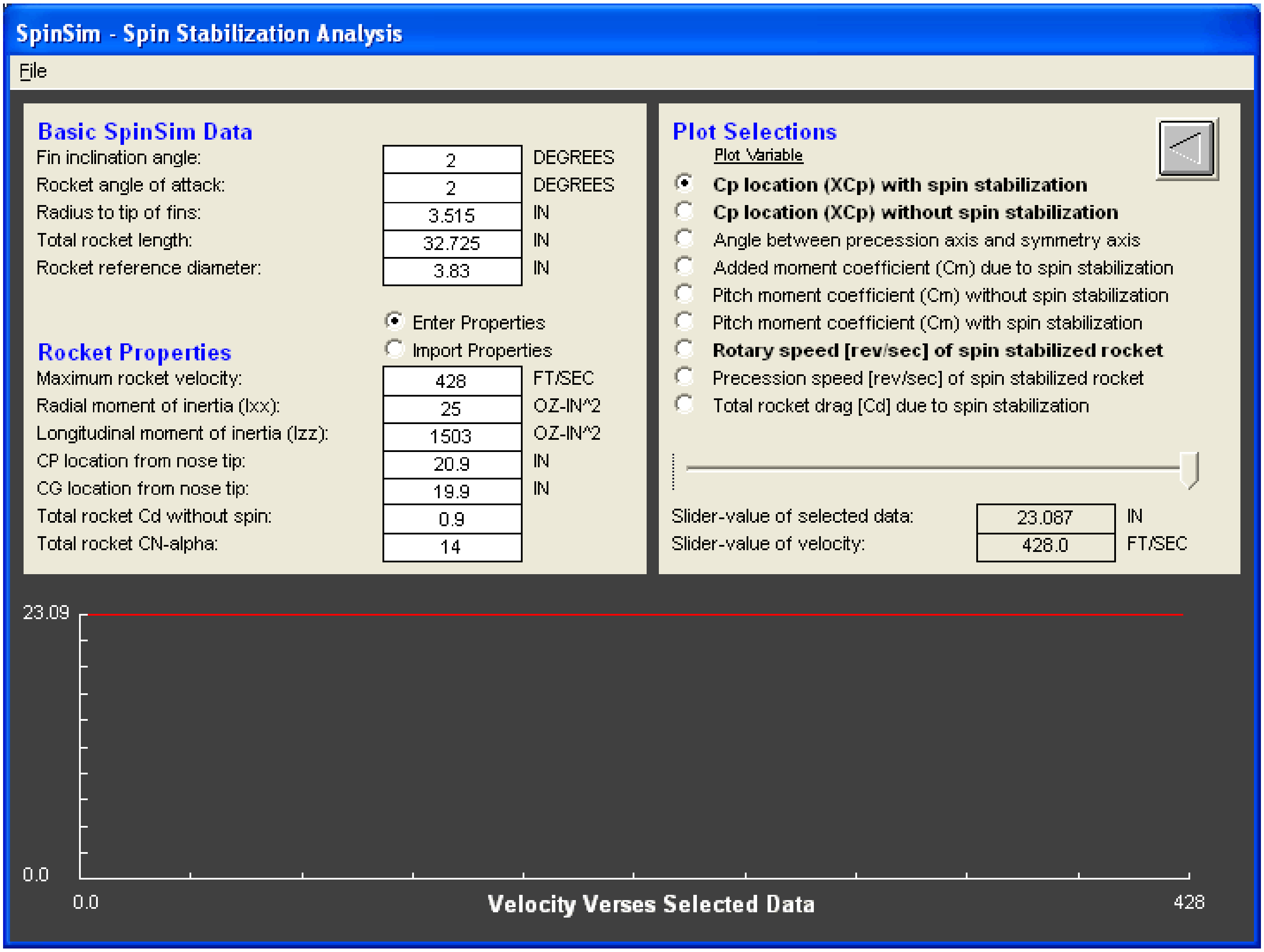


Figure-9: SpinSim Spin Stabilization Screen

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