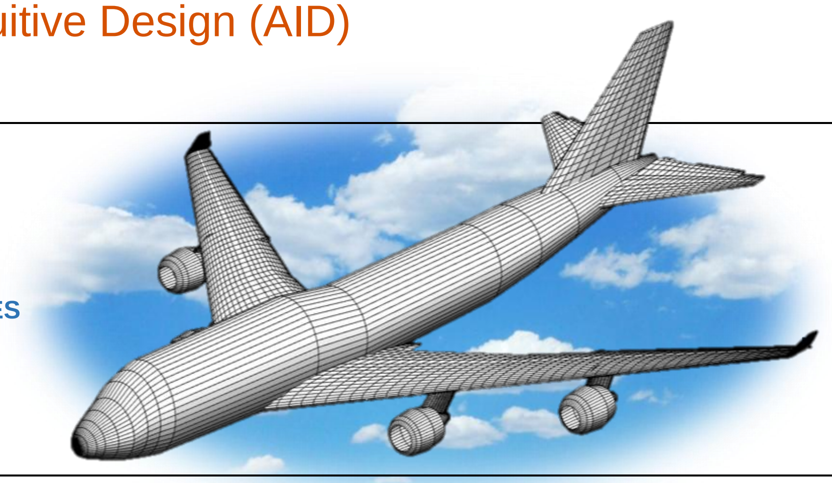
Aircraft Intuitive Design (AID)

Contents



Overview

AID is an academic tool intended to assist in developing an intuitive understanding of aircraft stability and control. By interfacing user-friendly aircraft modeling with rapid aerodynamic analysis, this program visually depicts how various design parameters affect the way an airplane flies.

Numerous geometric and aerodynamic parameters (i.e., planform shape, airfoil type, general configuration) must be tuned throughout the preliminary design phase, and knowing how these values influence a plane's stability is critical in making educated decisions to meet design goals. This program helps provide the user with this understanding, while also greatly reducing the time spent on trade studies between different wing/tail placements, planform shapes, and several other design considerations.

From the moment the program is first opened, several calculations have already been performed estimating the lift, drag, and moment of each planform and body, as well as many of the stability derivatives characterizing the aircrafts flight. In addition to these built-in, linearized stability approximations that are constantly being updated, the program interfaces with the following software for more advanced analysis:

- USAF Digital DATCOM
- Tornado Vortex Lattice Method
- AVL (Athena Vortex Lattice Method)

Note: While the majority of the inputs and outputs for these programs are written/read in automatically, the user is still encouraged to glance through the input/output files for errors by selecting **Settings > Inputs/Outputs**.

This program also gains added functionality from the following open source software:

- DATCOM Plot Interpolation Functions – Prof. Glen Greiner and Lenny Gartenberg (Embry-Riddle Aeronautical University, Daytona Beach, FL)
- AVL Input/Output Functions – Joseph Moster (Mathworks File Exchange)
- Datcomimport – MathWorks Aerospace Toolbox – loads DATCOM for006.dat
- NACA456 – Ralph Carmichael (PDAS) – NACA 6-series airfoil ordinates

Design

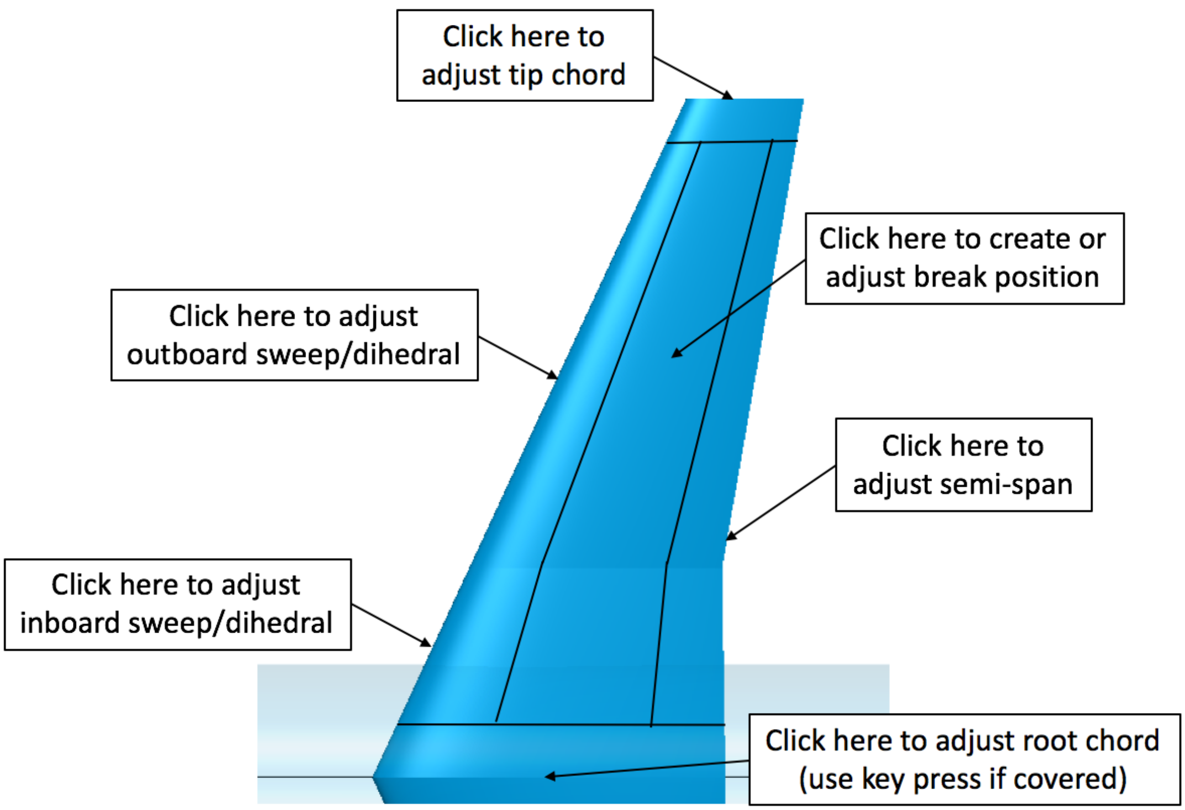
Interactive Controls (Aircraft Model)

When first opening the program, **try left clicking somewhere on the aircraft model**, for example on the wing tip (refer to the figure below or **Help > Quick Start** for an overview of what each clickable region corresponds to). Two things will happen:

1. Some sort of visual reference on the actual model will be highlighted with a black line (if you clicked on the wing tip, it will highlight the wing tip profile)
2. The input box for the selected parameter will be highlighted blue, indicating that it is ready to be adjusted (you could also click on the input box to select it directly)

Now, adjust the selected parameter by simply scrolling up or down.
Note: You can change the scroll sensitivity for most values by selecting **Settings > Scroll Sensitivity**.

To uncover or isolate a component, **hold down any key** (besides shift and space) after selecting its corresponding input tab. This is useful for selecting a planform's root chord.



Note: Clicking anywhere on the fuselage will allow you to adjust the shape parameter, *P*, of the nearest station. This parameter defines a modified super-ellipse or fermat curve for the fuselage cross-section. Essentially, *P*=1 gives a regular ellipse, higher values of *P* make the body more rectangular, and *P*=0 gives the cross-section of an SR-71.

Hold shift to drag individual components along reference axes and quickly adjust the airplane's configuration. For example, try holding shift to drag the wing up or down.

Double click on a body or planform to edit its cross-sectional shape. This feature is most commonly used for adjusting the fuselage. Your current view of the aircraft will decide whether to edit the side and top profiles, as described in the following section.

Right click a component to input weight and balance data.

General Controls: (These mouse controls apply universally throughout the program)

- Left click and drag to **rotate**
- Right click (on the model or a plot) and drag to **pan**
- Left click off body and scroll to **zoom**
- Right click anywhere off the body to
  - Reset the plot
  - Create a report (of some input/output variable or expression)
  - Adjust the view (side/top/front)
  - Load/Adjust a background image

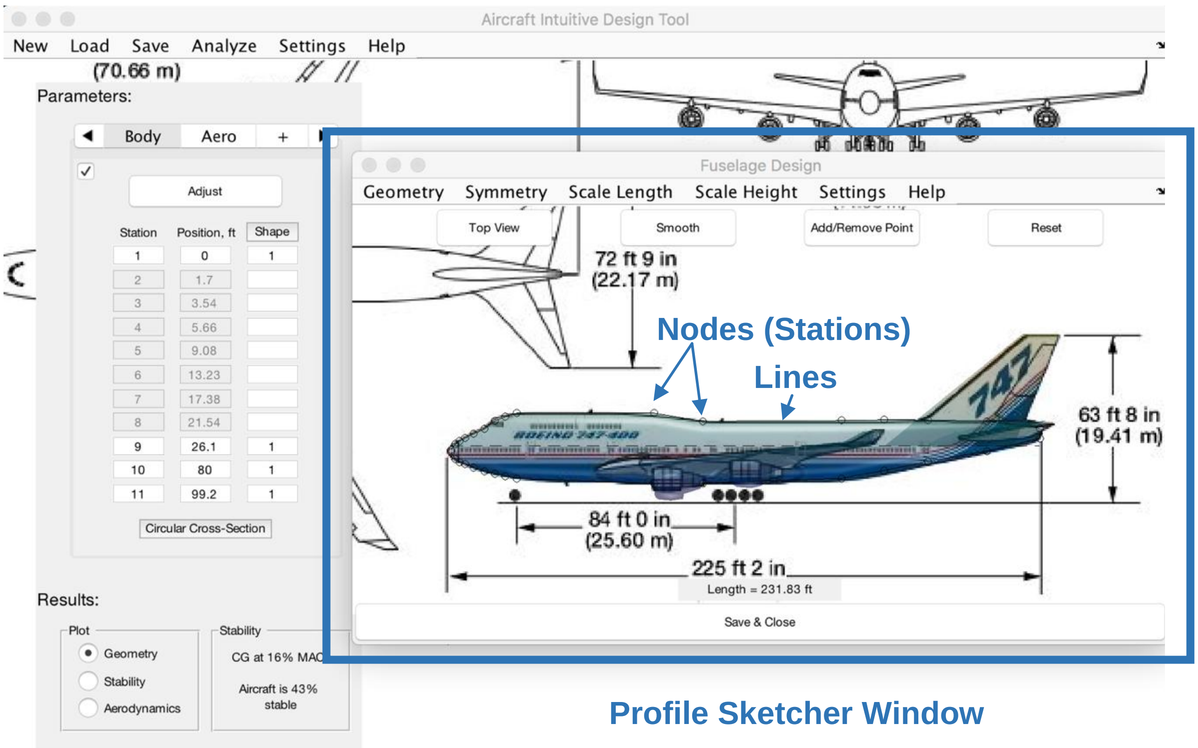
Cursor Tool

When rotating the model, your cursor will change into a little airplane indicating which profile you are currently working with. When it shows a side view of the airplane, double-clicking on the fuselage or any other body will allow you to edit the upper and lower surfaces from a side view. Conversely, a top view cursor indicates that you want to edit the width of each station. Lastly, the front view allows you to edit the dihedral of a planform by clicking on the leading edge, whereas clicking on the leading edge from any other view will select the planform sweep.

Cursor Symbol	Description
	Side View: Adjust side profile of fuselage/body
	Top View: Adjust top profile of fuselage/body
	Front View: Adjust planform dihedral (rather than sweep)

Profile Sketcher

Double clicking on any surface from the “Geometry” editor will load up a cross-sectional view of the body or planform, allowing you to edit its profile shape. This feature will most commonly be used to edit the fuselage and additional bodies, but can also be helpful in fine-tuning a planform’s root or tip airfoil shape.



Profile Sketcher Window

Profile Sketcher Controls: (These tips can also be found in **Help > Quick Start**)

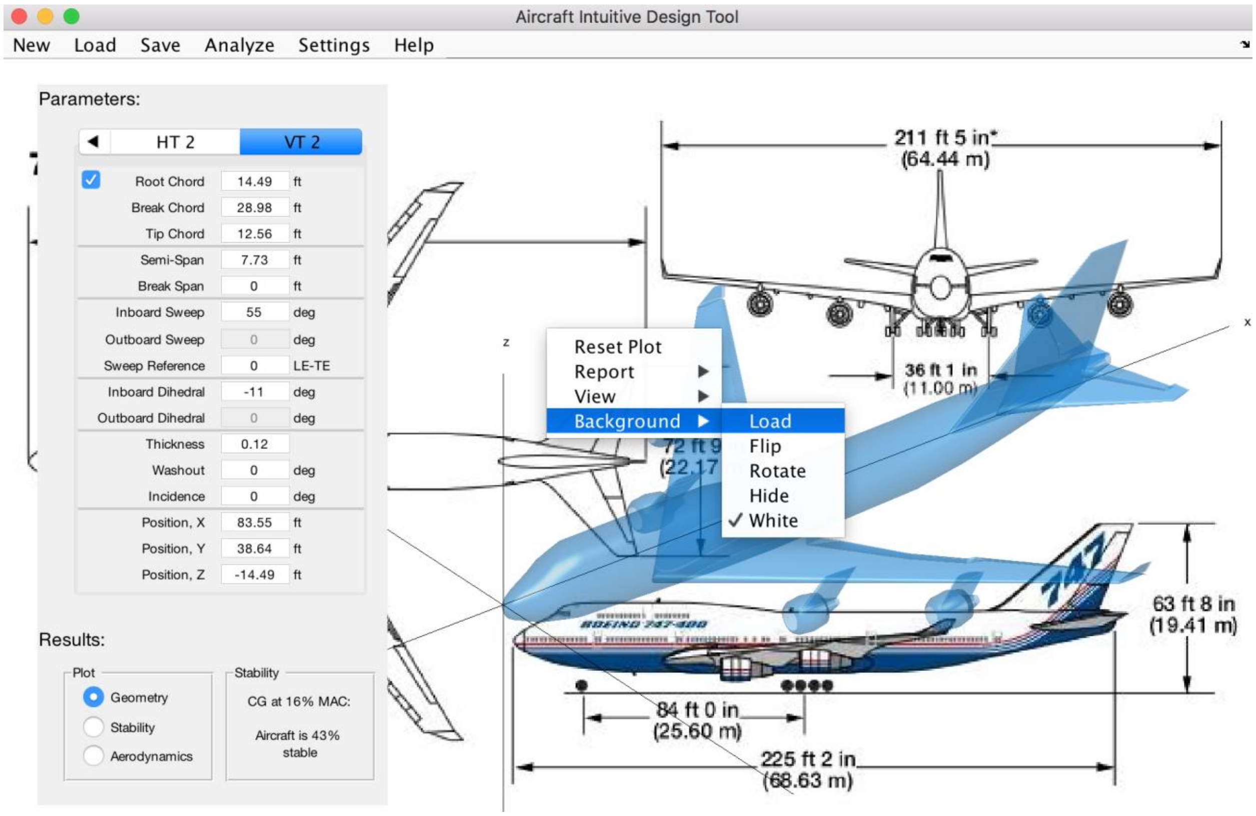
- Click and drag **nodes** to move individual points
- Click and drag **lines** to move segments vertically
- Click and drag **inside body** to move entire profile
- Click and drag **outside body** to move upper/lower surface
- Center/Shift click and drag **from a node** to "draw" profile
  Note: Using the option **Settings > Auto-Add Points** will create points where sharp gradients are detected.
- Center/shift click and drag **from inside/outside** body to select multiple nodes
- Click "Save" to update the model or simply close the window to cancel

Background Image

Right click anywhere on the figure background to pull up a list of options, then hover over the "Background" menu item and select "Load" to load an image file as the background.

Background Image Controls:

- Left click on the image and drag to (…you guessed it) **drag the image**
- Left click on the image and scroll to **zoom** (focused at your cursor location)
- Right click and hover over the "Background" menu item to
  - Flip the image horizontally
  - Rotate the image 90° counter-clockwise
  - Hide the image



Variable Assignments

You will notice throughout the program that certain default input values contain variable names. For example, if you create a spanwise break on the wing by either clicking on the center of the wing or adjusting the "Break Span" input, the outboard sweep and dihedral will automatically be set to their prescribed inboard values, "WG.SAVSI" and "WG.DHDADI", respectively. This means that rather than being given a single value, these parameters will update with the value of whatever variable they are assigned to.

There are two ways to quickly assign an input parameter to a variable without needing to type in the variable name.

1. **Leave the input box empty and press "Enter"**. The program will now wait for you to click on the quantity that you wish to set your input parameter equal to.
2. **Select a parameter by clicking directly on the model** (for example, the tip of the vertical tail), **press "Space"**, and **then select a different part of the model** (or an input value) you would like to set this parameter equal to (for example, the tip of the horizontal tail). Adjusting the variable that was assigned to your initial selection will, in turn, adjust your selected parameter.

For more advanced use, it would be advantageous to familiarize yourself with the variable names (listed in the appendix). Expressions using these variables can be evaluated from nearly any input box.

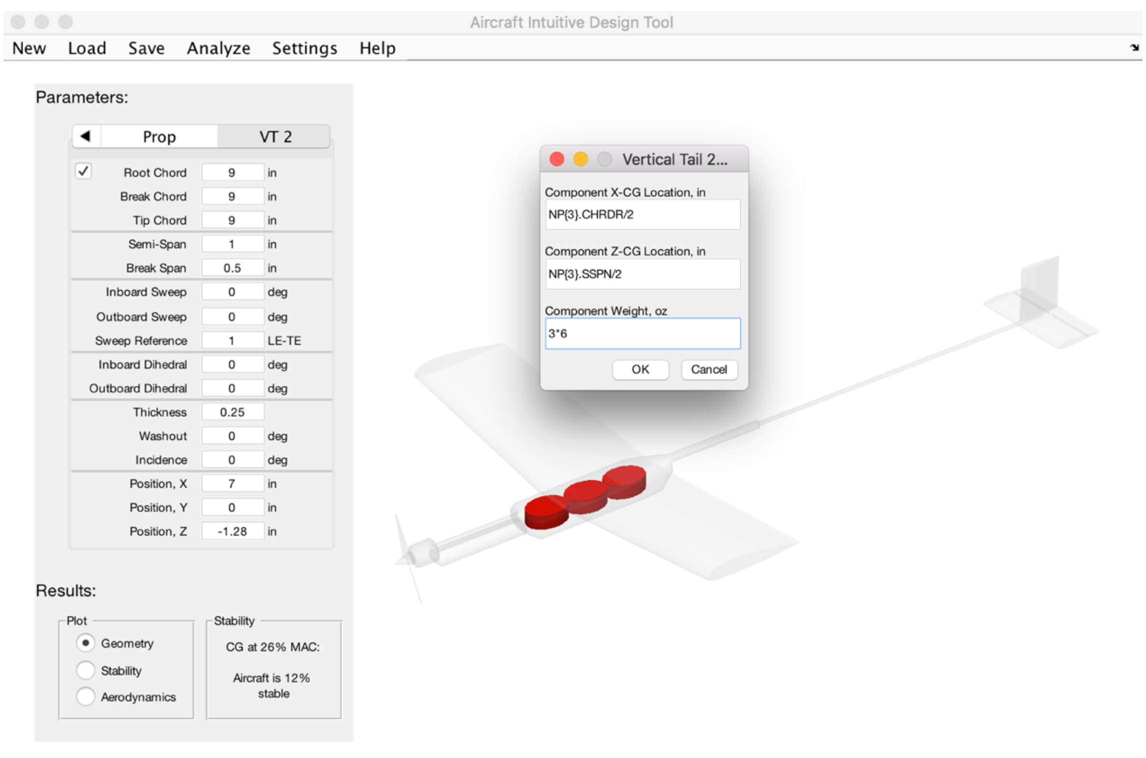
Weight and Balance

The aircraft weight and CG location can be prescribed in the "Aero" tab. Quickly jump to this tab by clicking on the background of the figure or on the "Results" box. The CG slider can be used to adjust the longitudinal position of the CG either as a percentage of the full fuselage length or of the MAC. Try varying the CG location while plotting the "Stability" results to see the effect CG location has on the stability slope.

If the weight of each planform and body can be estimated (either by judging from past designs or by estimating based on material density), **right click on each component to input weight and balance data**. The input dialog will request the X and Z location of the component's CG, relative to the datum (defined as either the apex of a planform or the nose of a body). In most cases, these values will already be set to some default expression (e.g., 33% or 50% MAC for the wing and tail planforms, respectively). The weight of the component can then be entered manually.

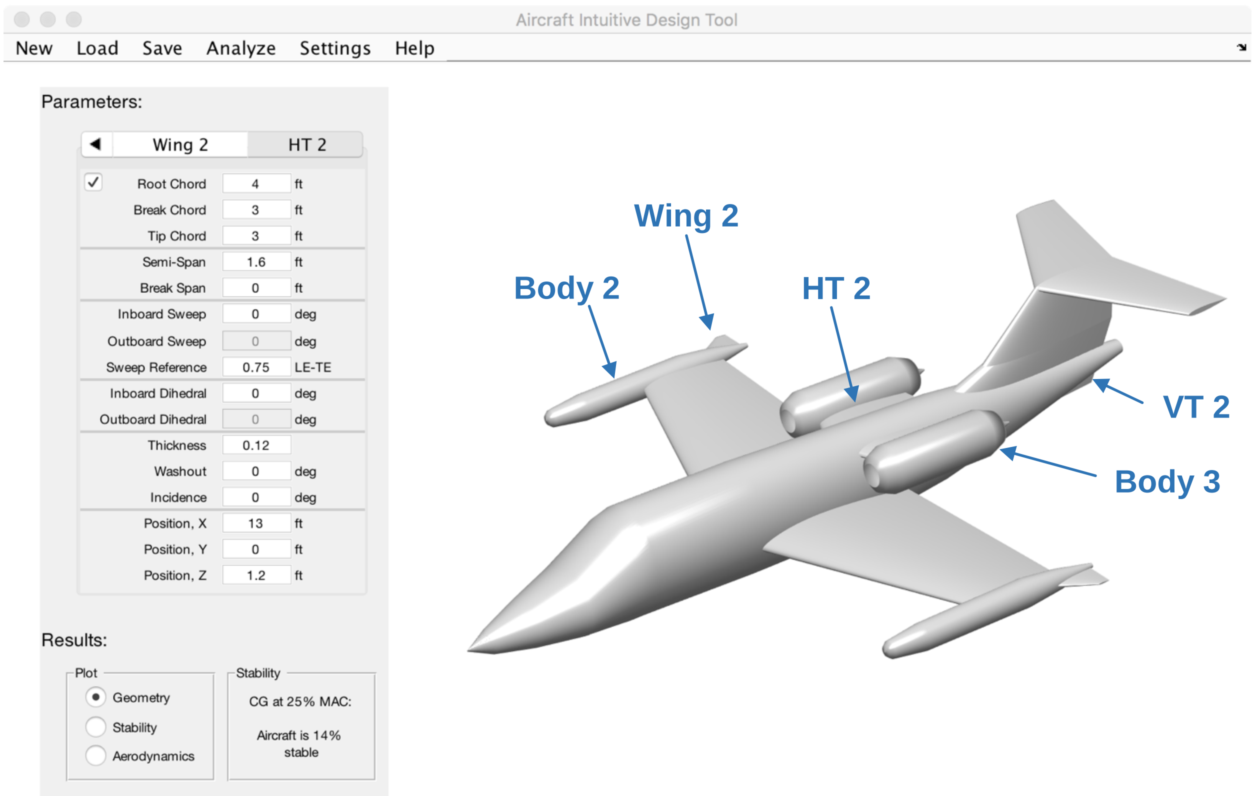
Use **Settings > Estimate CG** to calculate the aircraft's CG based on the prescribed component values. With this option turned on, using shift/center click to drag around components while watching the CG change can be exceptionally useful for configuration trade studies.

This example shows weight and balance data being input for a payload of three hockey pucks by right clicking on the component "VT 2" (after holding down a key to isolate it).
Note: The default units for weight inputs in this example are oz., but this can be changed via **Settings > Units**.



Added Components

The last tab, labeled “+”, can be used to create additional components. From this tab, the user can add up to two additional bodies, a propeller, and a second wing, horizontal tail, or vertical tail. These options can be creatively adapted to model various features such as engine nacelles, tip tanks, struts, winglets, landing gears, engine mounts, etc., as demonstrated in the model of a Learjet 23, below.



Additional components can improve **drag prediction** and are especially useful when performing **weight and balance calculations**, but the built-in stability approximations ***do not*** fully account for these extra planforms/bodies. Added planforms are, however, sent to Tornado and AVL when performing a numerical analysis of the lifting surfaces.

Overall, the intent of the user interface is to give as much functionality as possible while minimizing user inputs and avoiding unnecessary complexity. For example, the cell arrays “NP” and “NB” can easily be modified to allow for even more components to be added, and the functions “Plot_Planform.m” and “Plot_Body.m” can be modified with just a couple lines of code to plot non-linear distributions of chord, sweep, dihedral, twist, etc., and define fuselage cross-sections with arbitrarily complex parametric functions or even prescribed coordinates, but this would add little value to the analysis.

Analysis

Built-In Calculations

Upon opening the program, a small box in the lower left corner of the screen, labeled “Stability”, will state that as long as the CG is at 25% of the mean aerodynamic chord (MAC), the aircraft is 19% stable. This, of course, refers to the longitudinal, stick-fixed, static stability, implying a neutral point at roughly 44% MAC (the “19% stable” refers to the static margin being 19% MAC).

I want to emphasize that the calculations that arrived at this result are only approximations, and by no means am I distributing this program as an independent, validated analysis tool. These calculations simply combine various analytical and empirical methods for predicting aerodynamic behavior from sources such as Perkins and Hage, USAF DATCOM, and Pamadi. Thousands of other aerospace engineering students have written similar calculations in MATLAB, and my hope is that the code is modular enough for these users to swap out my analysis functions for their own if they so choose.

With that said, the methods I have included are fairly robust and they generally predict stability derivatives within the same ball park as other simplified analysis tools. More importantly, they accurately capture trends describing the effect of geometric variations on the stability derivatives. Listed here are a few especially helpful built-in calculations:

- **Trim Mode** – Calculate incidence angles or elevator deflection to trim for level flight at a prescribed gross weight and airspeed
  - Select **Settings > Calculations > Trim Mode**
  - Trim for planform incidence angles or elevator deflection
  - CG marker will turn yellow when max elevator deflection is exceeded (helpful in determining forward CG limit)
- **2-D airfoil characteristics** – Predict 2-D characteristics for arbitrary airfoil shapes (e.g., $C_{l_\alpha}, \alpha_{0L}, C_{m_{ac}}$) using a vortex panel method.
  - Input NACA designation in “Aero” tab or **enter “0” for more options**
- **Wake approximation** – Estimate the dynamic pressure ratio, η, and downwash gradient, $\frac{d\epsilon}{d\alpha}$, at the horizontal tail based on the wing wake geometry
  - Select **Settings > Calculations > Estimate Slipstream**
  - Plot “Aerodynamics” to visualize the wake
  - When disabling this option, η and $\frac{d\epsilon}{d\alpha}$ will need to be defined
- **Lift Distribution** – Predict the induced drag by calculating Glaurt’s numerical approximation of Prandtl’s lifting line distribution along the wing span
  - Plot “Aerodynamics” to view lift distribution (try comparing to Tornado results and use **Settings > Plot Options > Transparent** to view panels)
  - Check output variables WG.e, WG.K, and WG.spanwise

DATCOM

This code was originally created as a sort of DATCOM user interface, hence many of the variable names conform to to the DATCOM convention and the method for defining planforms and bodies is very similar to that of Digital DATCOM.

Digital DATCOM (derived from the USAF Stability and Control Data Compendium) is a Fortran program created back in 1976 in an attempt to consolidate existing methods for predicting aircraft stability and control. Unfortunately, the limited computing power available in the 70s reduced its capabilities, so some aircraft models will not be able to run in DATCOM due to restrictions on the number of fuselage stations, control surface deflections, etc. Still, it is a good benchmark analysis tool early in the design process.

According to the Digital DATCOM manual, "The fundamental purpose of the USAF Stability and Control Datcom is to provide a systematic summary of methods for estimating stability and control characteristics in preliminary design applications. Consistent with this philosophy, the development of the Digital Datcom computer program is an approach to provide rapid and economical estimation of aerodynamic stability and control characteristics." I mention this because it is in support of the same philosophy that I created this program.

Some notes when running a DATCOM analysis:

- Review the input file "for005.dat" by selecting **Settings > Inputs/Outputs**
- Only one control surface can be analyzed at a time in DATCOM (Elevator is default for full-configuration, if analyzing flaps, delete tail)
- Arrays are limited to 20 values (i.e., angles of attack, fuselage stations, etc.)
- Additional components cannot be analyzed by DATCOM, however, they can be written to a pseudo-DATCOM for005.dat file labeled "[*CaseID*] Parts.dat"

DATCOM results are saved to the structured array "**Results{1}**".

Tornado

Tornado is a vortex lattice method written by Tomas Melin at the Royal Institute of Technology (KTH). Because the code is written in MATLAB, it was very easy to implement and provided added functionality to this program. For example, the pressure distribution over each planform can be viewed in the "Aerodynamics" plot by selecting **Settings > Plot Options > Transparent** after running a Tornado analysis.

The user will be prompted for the number spanwise and chordwise nodes, be sure to check that the resulting panels accurately capture the flow gradients by monitoring the "Geometry" or "Aerodynamics" plots. Also check the simulation parameters (**Settings > Inputs/Outputs**) and pay special attention to the necessary conversions to SI units. Tornado results are saved to the structured array "**Results{3}**".

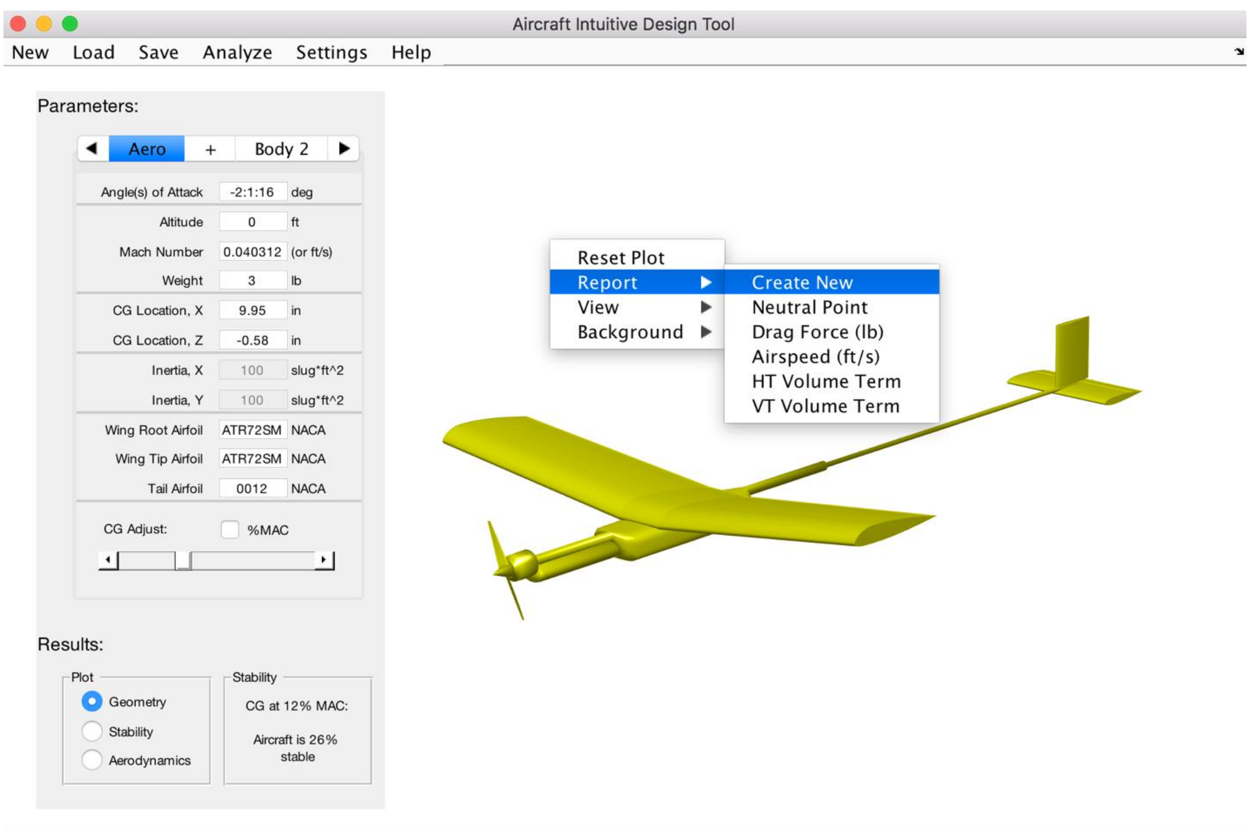
AVL

AVL is a vortex lattice method written by Mark Drela (author of XFOIL) and Harold Youngren at MIT. As with the other software, the user is encouraged to check each input and output file (**Settings > Inputs/Outputs**) to ensure that it accurately represents the aircraft model and performs the desired analysis. The output files are read in using a set of functions provided on the Mathworks File Exchange labeled "Aerospace Design Toolbox" by Joseph Moster. AVL results are saved to the structured array "**Results{4}**".

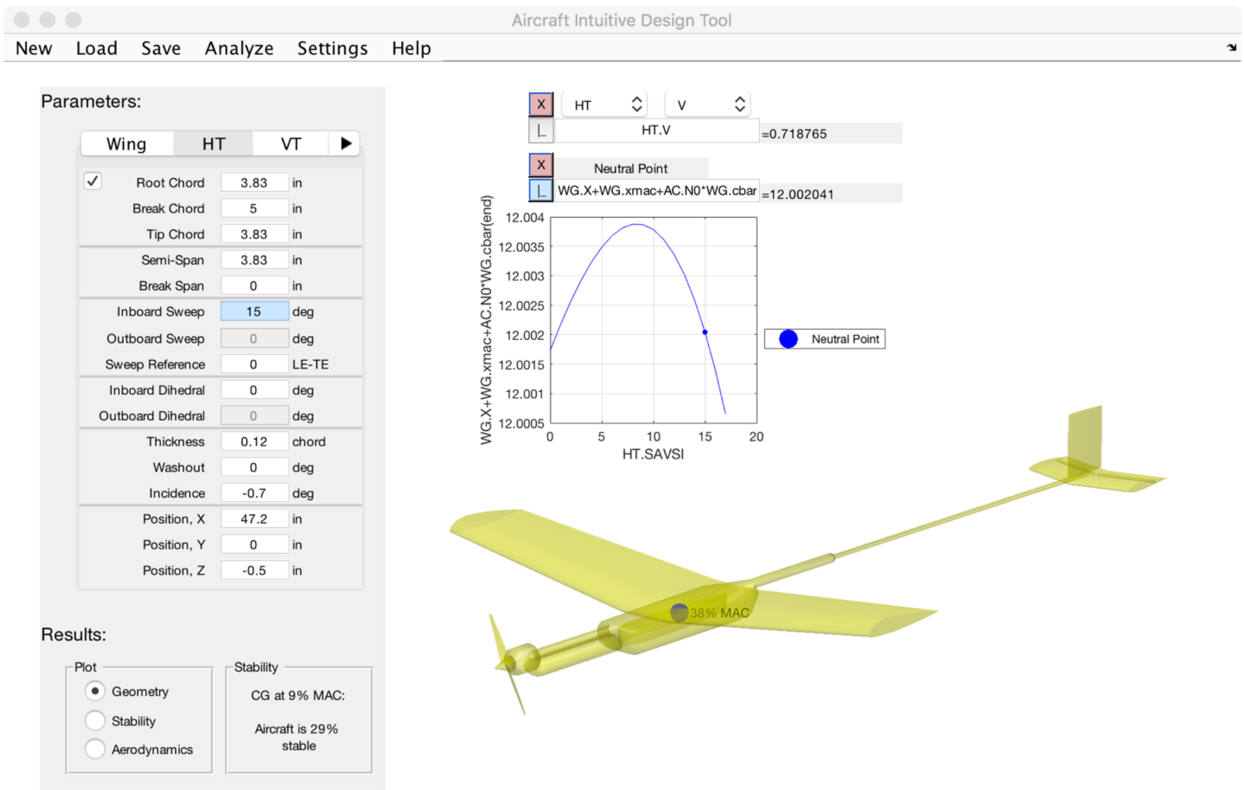
Reporting Results

The quickest way to check a specific output quantity is to generate a report. To do this, **right click** on the figure in the location where you would like the report to appear, hover over the "**Report**" option, and select the "**Create New**" menu item or one of the other default options.

Choose an output variable by selecting from the dropdown menus or typing the variable name into the edit box directly. For example, try reporting **WG.AR** (the aspect ratio of the wing). **Click the plot button** to the left of the edit box, then select some input parameter (try the wing tip) and scroll up/down to see how it affects the reported value.



Remember that **the plots and report boxes can be dragged around using right click**, just like everything else**.** This method of cost analysis can be used to quickly assess the influence of adjusting various parameters. It becomes very useful when monitoring multiple outputs, as in the example below, where the sweep of the horizontal tail is considered with respect to tail volume coefficient and neutral point.



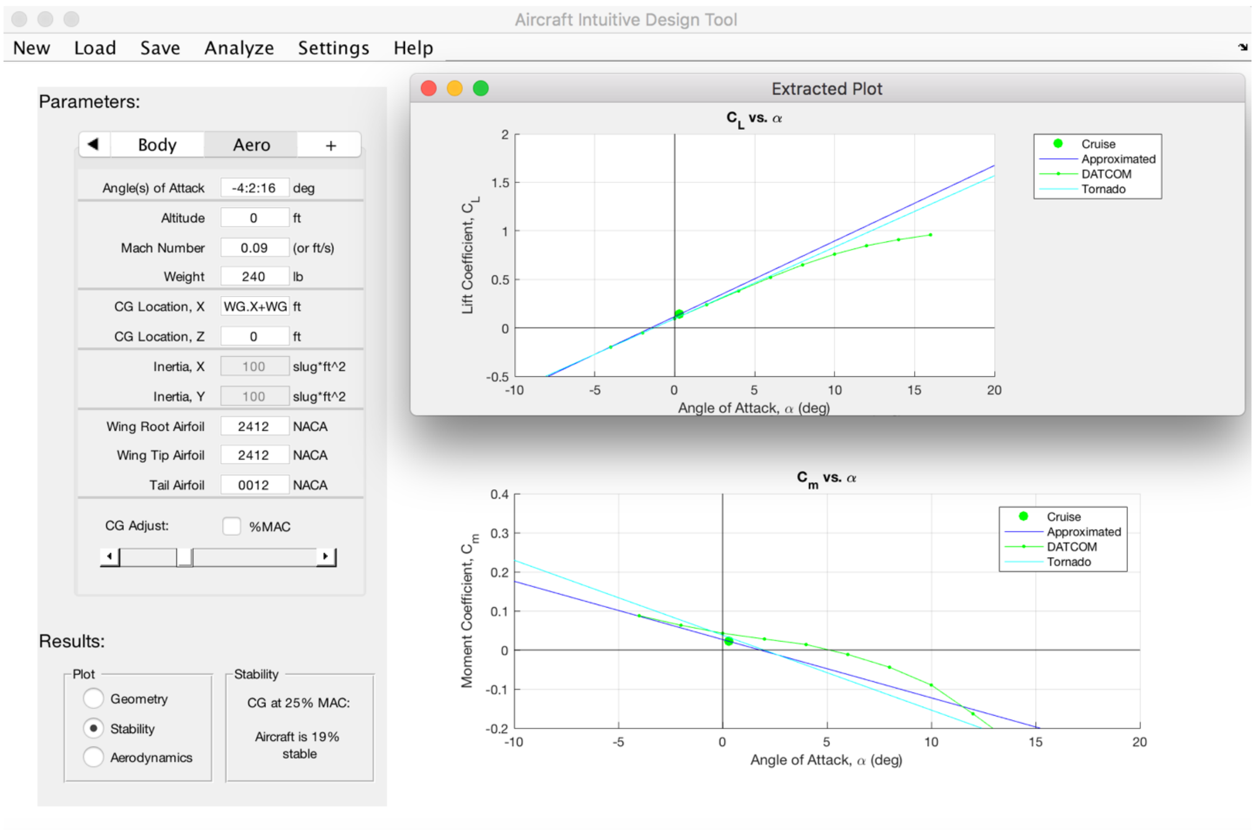
Another way to quickly assess the longitudinal stability of the aircraft is to run each analysis method and compare the results in the "Stability" plots. The complete list of results can be found in the "**AC**" and "**Results**" cell arrays. For example, report Results{1}.cl to print the DATCOM C_L values at whatever angles of attack were prescribed in the "Aero" tab when you ran the analysis. The following table summarizes where each set of result variables can be found.

Structure Name	Description
AC	Built-in linearized analysis using various methods
Results{1}	DATCOM Output Variables
~~Results{2}~~	~~ASCDM Output Variables~~
Results{3}	Tornado Output Variables
Results{4}	AVL Output Variables

I chose to leave the user with the option of writing their own function to compare whatever results they are interested in. However, I included an example function labeled "Plot_Results.m" that can be used by uncommenting lines 115-121 of "Initialize_GUI.m"

Interactive Controls (2-D Plots)

Interactive controls for each of the plots are similar to those used to adjust the model. **Right click to drag a plot**, then **scroll to zoom** in and out with the reference point being the cursor position. **Double click any plot to “extract” it**. This will create a separate figure for the plot, and print the axes handle to the command window so it can be formatted however the user chooses.



For conventional aircraft designs, you can **left click and drag the operating point** (big green dot) on a lift curve slope or stability slope plot.

- Dragging the point vertically on the lift curve slope plot will automatically set the **flap deflection** to match the desired **lift coefficient**
- Dragging the point vertically on the stability slope plot will set the **elevator deflection** to match the desired **moment coefficient** (usually easier to just turn on trim mode and have the moment default to zero to maintain proper balance)
- Dragging the point horizontally on either plot will set the the **airspeed** to allow for the desired **angle of attack** while maintaining level flight.

Future Work

Dynamic Stability

While the static, longitudinal stability predictions are generally consistent between each analysis method, and the static, lateral/directional stability and control derivatives often agree with moderate variation, the dynamic stability derivatives, even compared between external analysis methods, concur far less frequently. This is to say that the calculations for predicting dynamic stability derivatives are not very reliable.

Fortunately, at the design phase that this program is intended for, a dynamic stability analysis is only required to ensure each mode is sufficiently damped, rather than accurately quantify the frequency of the phugoid mode or perform other detailed numerical predictions. Still dynamic stability is an area that could use some work as far as validating results and gathering a complete set of inertia inputs in a simple and intuitive manner. Once these values can be approximated with some certainty (and the inertia inputs can be trusted as well) they can be used to calculate the aircraft's handling qualities on the Cooper–Harper rating scale.

Thrust/Power Considerations

With predictions of the induced and parasite drag of the aircraft being readily available, it would make sense to now implement some sort of thrust calculation. This can be as simple as a user input for a thrust/power range (for jet or propeller-driven aircraft, respectively), or as in-depth as a calculation for a given propeller geometry throughout a prescribed range of RPM settings and airspeeds (i.e., advance ratios).

Another note here is that the propeller's effect on drag and stability has not been fully accounted for by the built-in calculations. This could be handled by calculating the blade properties from the user inputs for incidence and washout, and then performing the necessary calculations to predict the effect of the thrust vector, prop-wash, P-factor, etc., on the overall stability and handling characteristics.

Flight Simulation

Lastly, once the previous two areas are addressed, the plane can be accurately modeled in a flight simulator. This has already been done with improvised thrust settings by linking a Simulink 6-DOF model to the flight simulator, FlightGear, using the calculated stability derivatives. Incorporating this feature in real-time provides by far the most intuitive method for analyzing the aircrafts flight characteristics, the only drawback is that it requires some setup with assigning the necessary quantities to the base workspace and then jumping back and forth between Simulink and the MATLAB script for each update cycle. The user can set this up using a suitable Simulink model by uncommenting line 128 of "Initialize_GUI.m" and editing the function "Input_Sim.m".

Appendix: Variable Names

Planforms

Structure Name	Description
WG	Main Wing
HT	Horizontal Tail (Horizontal Stabilizer)
VT	Vertical Tail (Vertical Stabilizer or Fin)
NP{1}	Secondary Wing
NP{2}	Secondary Horizontal Tail
NP{3}	Secondary Vertical Tail
NP{4}	Propeller

Field Name	Description
CHRDR	Root Chord
CHRDBP	Break Chord
CHRDTP	Tip Chord
SSPN	Semi-Span
SSPNE	Semi-Span Exposed (for drag predictions)
SSPNOP	Break Span
SAVSI	Inboard Sweep
SAVSO	Outboard Sweep
CHSTAT	Sweep Reference
DHDADI	Inboard Dihedral
DHDADO	Outboard Dihedral
TC	Thickness
TWISTA	Washout Angle (Negative Twist)
i	Incidence Angle
X, Y, Z	Leading Edge Position of Planform Root (Apex)
b	Span
TR	Taper Ratio (Inboard, Outboard, Combined)
S	Planform Area (Inboard, Outboard, Combined)
AR	Aspect Ratio (Inboard, Outboard, Combined)
gamma	Dihedral, Γ
swp	Sweep at LE, 25% chord, 50% chord, and TE, Λ
Xbrk, Ybrk, Zbrk	Leading Edge Position of Planform Break
Xtip, Ytip, Ztip	Leading Edge Position of Planform Tip
cbar	Mean Aerodynamic Chord (MAC)
xmac	Position of MAC (approximated as being equal to MGC)
ymac	Spanwise Position of MAC
x_ac	Aerodynamic Center (percentage of MAC)
NACA	NACA Airfoil Designation for Root and Tip
DATA	Airfoil Ordinates for Root and Tip
a0	2-D Lift Curve Slope, C_{l_α}
alpha0	2-D Zero-Lift Angle, α_{0_L}
Cm_ac	2-D Moment Coefficient about Aerodynamic Center, $C_{m_{ac}}$
a	3-D Lift Curve Slope, C_{L_α}
alpha0L	3-D Zero-Lift Angle, α_{0_L}

Cm	3-D Moment Coefficient about Aerodynamic Center, $C_{m_{ac}}$
CL	Lift Coefficient, C_L
CL0	Lift Coefficient, C_L, at $\alpha = 0°$
CD0	Parasite Drag Coefficient
Cm0	Moment Coefficient, C_M, at $\alpha = 0°$
e0	Planform Efficiency Factor (not including interference)
e	Oswald's Efficiency Factor
K	Induced Drag Coefficient ($C_D = C_{D0} + KC_L{}^2$)
spanwise	Spanwise Lift Distribution (Structured Array)
dwash	Downwash gradient, $d\epsilon/d\alpha$
eta	Dynamic Pressure Ratio, η
l	Tail Length Term
V	Tail Volume Coefficient
XCG	Component X-CG Location
ZCG	Component Z-CG Location
WT	Component Weight

Bodies

Structure Name	Description
BD	Fuselage (Primary Body)
NB{1}	Secondary Body
NB{2}	Tertiary Body

Field Name	Description
NX	Number of Stations
X	Longitudinal Station Coordinates
ZU	Upper Station Coordinates
ZL	Lower Station Coordinates
R	Station Half-Widths
S	Station Cross-Sectional Areas
N	Control Point Array (for Limited Station Controls)
P	Shape Parameter (SR-71 – Ellipse – Rectangle)
d_eq	Equivalent Diameter at Root Chord
dk	Monk's Apparent Mass Factor
CD0	Minimum Drag Coefficient
Cm0	Parasite Drag Coefficient
Cma	Stability Slope
Cnb	Weathervane Stability Slope
X0, Y0, Z0	Position of Nose (Reference Point)
XCG	Component X-CG Location
ZCG	Component Z-CG Location
WT	Component Weight

Simulation Parameters

Structure Name	Description
AERO	Flight Conditions

Field Name	Description
ALSCHD	Array of Angles of Attack, α (deg)
ALT	Altitude (ft)
MACH	Mach Number
WT	Gross Weight
XCG	X-CG Location
ZCG	Z-CG Location

Structure Name	Description
ATM	Atmospheric Conditions

Field Name	Description
T	Temperature (R)
P	Pressure (psf)
D	Density (slug/ft^3)
V	Viscocity, μ (lb*s/ft^2)
a	Speed of Sound (ft/s)
Q	Dynamic Pressure, $1/2\ \rho V^2$ (psf)
Re	Reynolds Number per Unit Length, Re/L