Tapered Keel Analysis

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Introduction

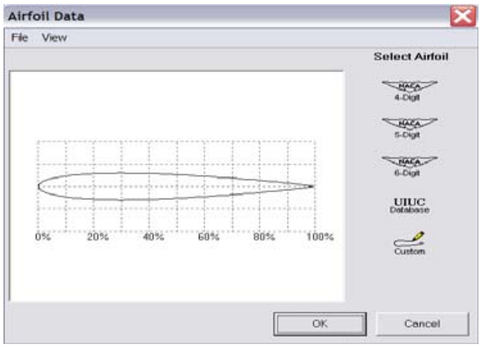
3DFoil is a powerful software package that can be used to analyze airfoils sections and 3-Dimensional wings and hydrofoils. The software can be used to test custom airfoils in addition to airfoils from its built-in library of NACA 4, 5 & 6-digit airfoils. 3DFoil also includes over 1000 airfoils found in the UIUC airfoil database.

3DFoil's main function is 3-dimensional wing and hydrofoil analysis and design. For 3-dimensional analysis, the software uses a vortex lattice method based on vortex rings to compute the lift and induced drag for wings with arbitrary cross section shapes (at wing root and tips), linear twist, camber and dihedral angles. Profile drag is estimated using a vortex panel method coupled with a boundary layer solver applied at a designated cross section of the wing.

Wings designed using 3DFoil can be exported to a CAD file using the ASCII .STL format. This format is readable by many popular CAD and CAE software packages (including Stallion 3D). In addition, the .STL file can be used to construct a prototype of the wing using a 3D printing machine.

Built-in Airfoil Analysis Tool

In this section, we will analyze and compare the results from three airfoils sections using 3DFoil airfoil analysis tool. The user can select an airfoil from the Airfoil Analysis/Select Airfoil Menu. This will invoke the airfoil selection dialog box shown below:



The dialog box can be used to select NACA 4, 5 & 6-Digit airfoils in addition to airfoils from the UIUC airfoil database and custom shapes.

Once the airfoil is selected the program has a variety of analysis and graphing functions that can be used to test the performance of a single airfoil or compare the performance of multiple airfoil shapes.

Figure 1 shows the pressure distribution at the surface of a NACA 0012 airfoil at angles of attack of 0, 5 and 10 degrees. This graph was created in 3DFoil and simply pasted in this report. 3DFoil graphing functions also include custom labeling, scaling, annotations and legends.

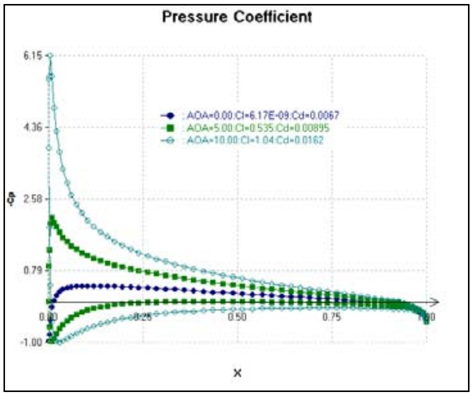


Figure 1. Pressure Coefficient Graph

3DFoil's airfoil analysis tool can also be used to compute the lift coefficient and profile drag coefficients for an angle of attack sweep. Figures 2 and 3 compare the performance of NACA 0012, NACA 2412 and NACA 64-412 airfoils at a Reynolds number of one million.

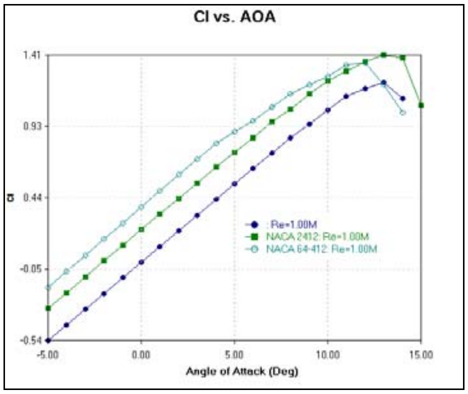


Figure 2. Lift Coefficient Versus Angle of Attack

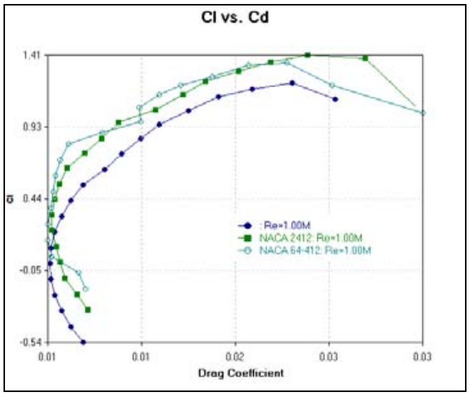


Figure 3. Lift Coefficient Versus Drag Coefficient

Other functions and graphs under the airfoil analysis tool menu include surface velocity ratio versus chord and cavitation number plotted with surface pressure coefficient.

Keel Analysis

Tapered keels and rudders can be readily analyzed in 3DFoil. In the following sections, we will analyze the tapered keel shown below in Figure 4. (**Note:** the following steps are identical for ***MultiSurface Aerodynamics***.) We will use 3DFoil to investigate how two different sweep angles affect the lift, drag and the location of the **center of lateral resistance** for a new keel design.

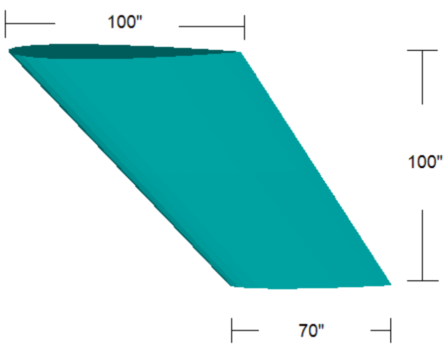


Figure 4: Tapered Keel

Keel Planform Setup

We start the tutorial by entering the keel dimensions into 3DFoil. To do this, click on the **Design** menu followed by the Top Elevation option. This will invoke the Surface Editor screen shown below in Figure 5. The surface editor shows the default wing which is a 1m X 1m square surface.

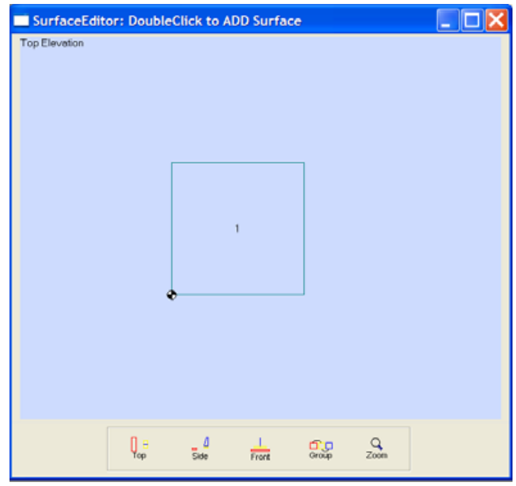


Figure 5: The SurfaceEditor

The next step is to change the default surface into the keel of interest. To do this, double-click within the boundary of surface no. 1 on the SurfaceEditor screen to invoke the Edit Surface window show below in Figure 6.

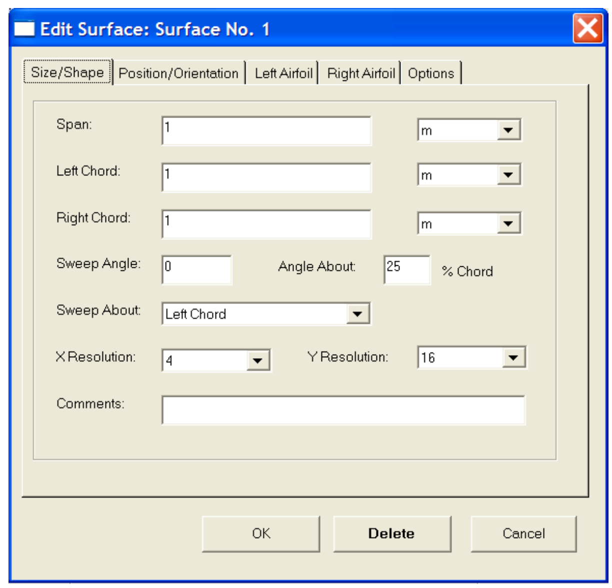


Figure 6: Edit Surface Dialog Box

In the Edit Surface window, change the Span value to 100 and the span unit of dimension from meters (m) to inches (in). We choose to make the right chord the root of the keel and the left chord the tip. In the dialog box, change the Right Chord value to 100 and the unit of dimension from meters (m) to inches (in). Next, change the Left Chord dimension and unit to 70 and inches respectively.

For this tutorial, we wish to analyze sweep angles of 30 and 45 degrees. For the first investigation, set the sweep angle to 30 degrees in the Sweep Angle box. The sweep is about the 25% chord line so you must set the About Angle box to 25 % of chord. 3DFoil allows you the option of setting the sweep about the left or right tips of the keel. Here, choose the right tip and click on the right tip option in the Edit Surface dialog box. Figure 7 shows the new setting as they now appear in the Edit Surface dialog box.

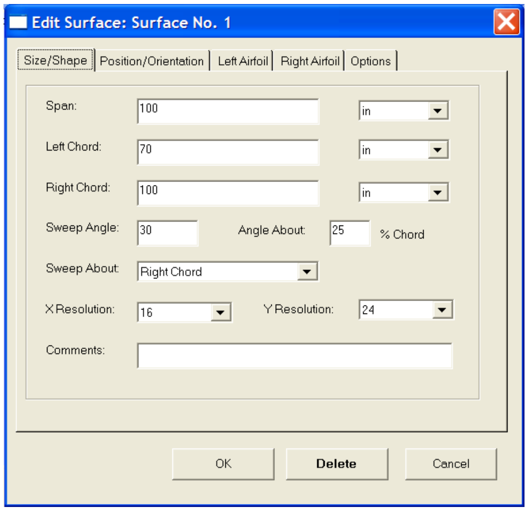


Figure 7: Edit Surface Size/Shape Settings

Airfoil Settings

The keel (see Figure 4) has an 18% thick airfoil at the root chord and a 12% thick airfoils at the tip chord. To set the airfoil at the root chord, select the Right Airfoil tab on the Edit Surface dialog box as shown in Figure 8. To change the default airfoil from the NACA 0012 to NACA 0018, click on the right airfoil **Select** button. The select button invokes the Airfoil Data dialog box shown in Figure 9. To set the NACA 0018 airfoil, click on the NACA 4-Digit Airfoil button to invoke the NACA 4-Digit Airfoils dialog box. Figure 10 shows the NACA 4-Digit airfoil dialog box. Use the list boxes to choose the desired airfoil number. In this case it is the NACA 0018.

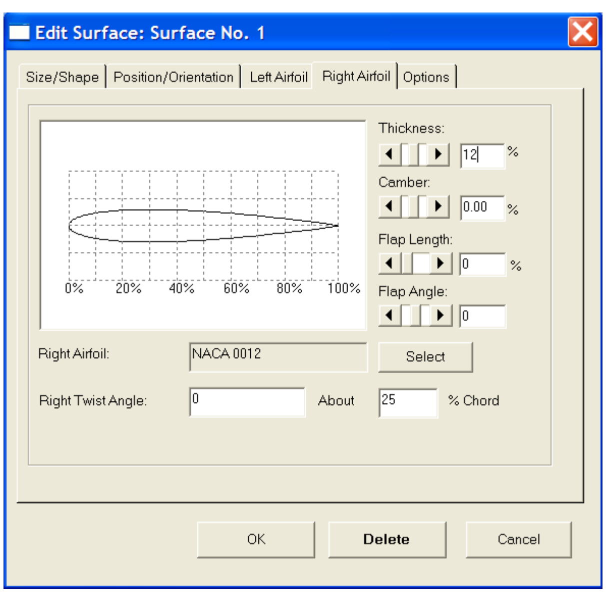


Figure 8: Right Airfoil Tab

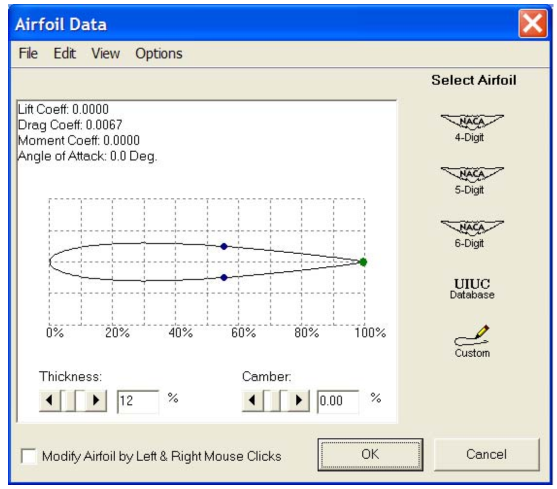


Figure 9: Airfoil Data Dialog Box

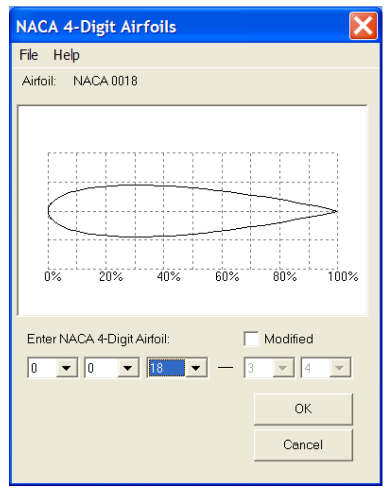


Figure 10: NACA 4-Digit Airfoils Dialog Box

After setting the airfoil for the root, click on the Left Airfoil Tab of the Edit Surface dialog box and repeat the airfoil selection procedure for the airfoil at the tip of the keel. In the NACA 4-Digit Airfoils dialog box (see figure 10), select the NACA 0012 airfoil for the tip instead of the NACA 0018.

Figure 11 shows the plan view of the keel as seen in the SurfaceEditor window.

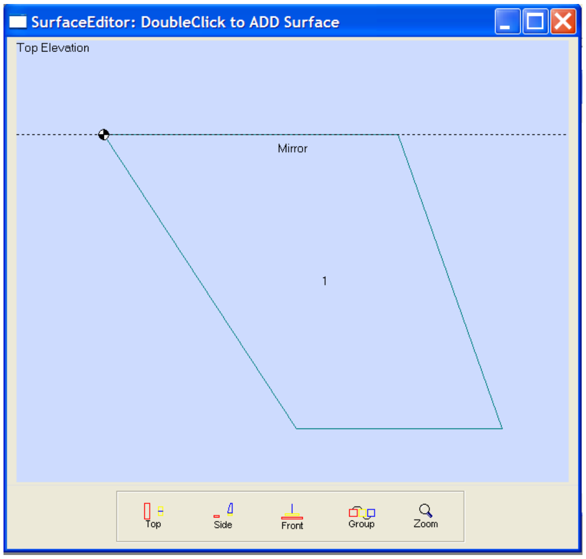


Figure 11: Planform view of the keel.

Flow Field Settings

We now wish to choose the fluid type (water) and set the speed of the boat. To do this, click on the **Flow Field** menu and select the **Flow Field Conditions** option. This invokes the Flow Field Conditions dialog box shown below in Figure 12.

To set an angle of attack of 5 degrees, enter 5 in the Angle of Attack box. To set a speed of 10 knots, enter 10 in the Speed box and select units of knots.

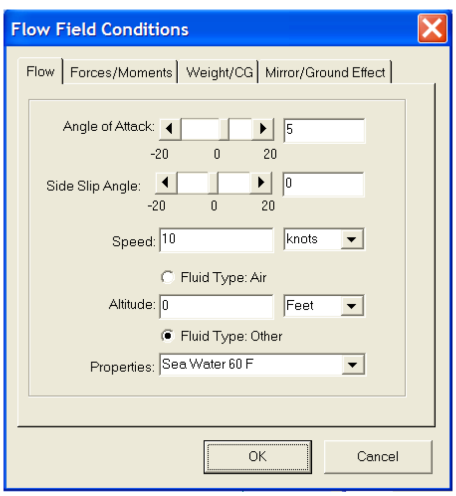


Figure 12: Flow Field Condition Dialog Box

To set water as the fluid, select the **Fluid Type: Other** button and then select properties of Sea Water 60 Degrees F. The user can select a variety of fluid properties and has the choice of entering a table of water densities, viscosities and vapor pressures.

Click on the **Forces/Moments** tab to set the results units as shown below in Figure 13. First, set the moment Reference length to 1 meter. The reference length is used in all moment coefficient calculations. Since we wish to display force results in pounds, set the Force Units to Pounds. Set the Length Unit to inches to display the length results in inches. The speed results are displayed in the speed units selected under the Flow tab.

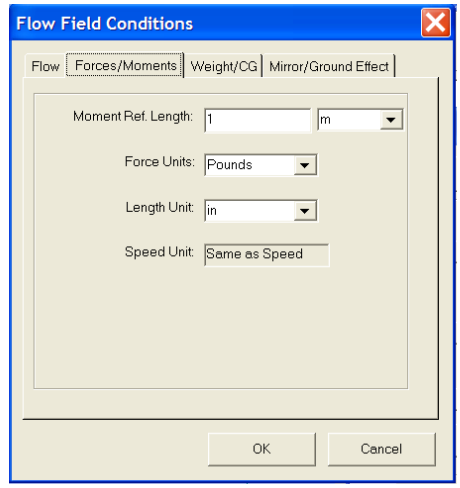


Figure 13: The Force/Moments Tab is used to set the Display Units.

Center of Gravity Settings

The center of gravity location is used a reference point and datum for moment calculations and center of pressure measurements. To use the origin as the center of gravity, click on the Weight/CG tab as shown below in Figure 14. Set the X-Distance, Y-Distance and Z-Distance boxes to zero. This (0,0,0) setting will place the reference point at the leading edge of the root chord of our keel.

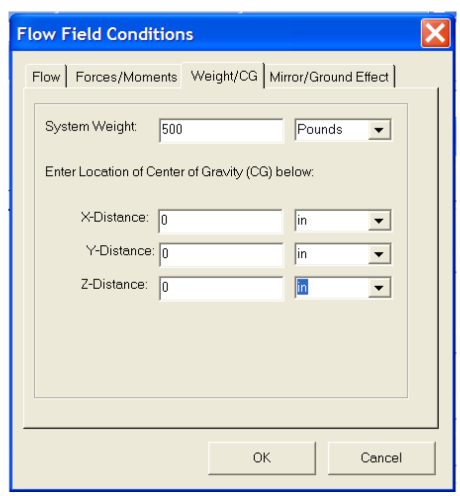


Figure 14: The CG Locations is used as a reference point.

Modeling the Hull

Since the root chord of the keel is attached directly to the hull, it must be modeled as a reflective plane. Click on the Mirror/Ground Effect tab of the **Flow Conditions** dialog box as shown below in Figure 15. Next, click on the **Mirror Image in X-Z Plane** setting to select the radio button. Figure 11 shows the line of symmetry (labeled mirror) that models the hull.

Results and Graphs

The lift coefficient versus angle of attack graph shows the lift (lateral resistance) developed by the keel as the angle of attack (leeway angle) increases. With the sweep back setting of 30 degrees, click on the **Surface Analysis** menu and **Cl vs AOA** option. Next, set the sweep back angle to 45 degrees and again click on the **Surface Analysis** menu and the **Cl vs AOA** option. This will produce the graph of Cl vs AOA as shown below in Figure 16. The graph shows that the lift with 30 degrees angle of sweep is higher than with 45 degrees angle of sweep for corresponding angles of attack. Click on the **Surface Analysis** menu and the **Cl vs Cd** option to obtain the lift-drag polar for the keel as shown below in Figure 17.

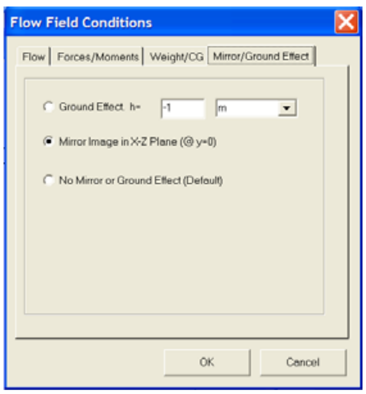


Figure 15: Modeling the hull with the mirror image setting.

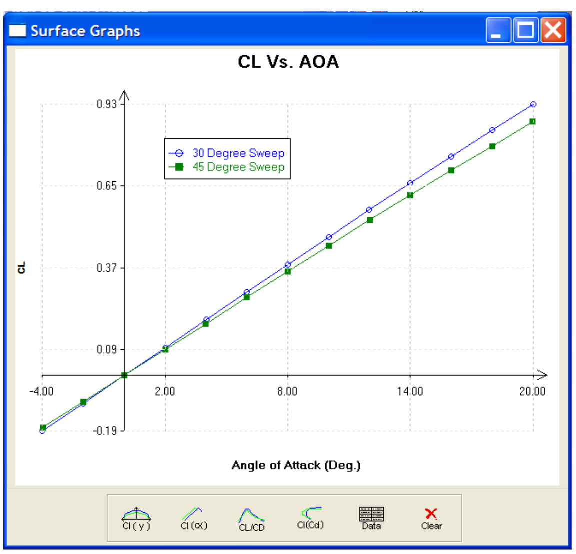


Figure 16: Lift Coefficient vs Angle of Attack

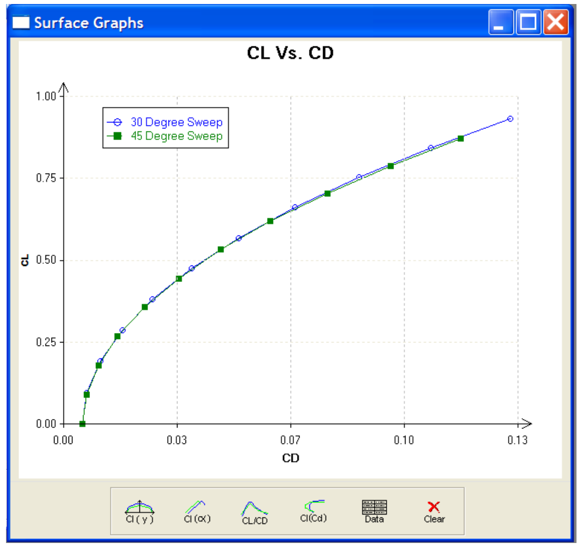


Figure 17: Lift Coefficient vs Drag Coefficient

We can use the **Reports** menu and the **Results Summary Table** option to create a comparison chart of the keel's performance at a desired set of angles of attack. Figure 18 shows the results for the 30 degrees sweep back angle at the speed of 10 knots. 3DFoil computes lift, drag and moments about the reference location (CG). The program computes the center of lateral resistance for the keel as well. The x-component (horizontal value) is obtained by dividing the pitching moment by the lift. The y-component (depth) is obtained by dividing the roll moment by the lift. The results place the center of lateral resistance a distance of about 49 inches from the keel root leading edge and 44 inches in depth.

Results Summary

	Angle = 0 Deg	Angle = 2 Deg	Angle = 4 Deg	Angle = 6 Deg	Angle = 8 Deg
Total Lift (Pounds)	0.00	1,603.28	3,204.61	4,802.03	6,393.61
Total Side Force (Pounds)	0.00	0.00	0.00	0.00	0.00
Total Drag (Pounds)	89.93	111.00	176.18	281.20	426.60
Body Lift (Pounds)	0.00	0.00	0.00	0.00	0.00
Body Side Force (Pounds)	0.00	0.00	0.00	0.00	0.00
Body Drag (Pounds)	0.00	0.00	0.00	0.00	0.00
Moment (Pound-ft, CG)	0.00	-6515.0127	-13023.5226	-19518.8748	-25994.1114
Roll Moment (Pound-ft, CG)	0.00	5,857.05	11,685.56	17,457.15	23,143.68
Yaw Moment (Pound-ft, CG)	0.00	0.00	0.00	0.00	0.00
Lift Coeff.	0.00	0.0957	0.191	0.287	0.382
Side Force Coeff.	0.00	0.00	0.00	0.00	0.00
Induced CD	0.00	0.00123	0.00492	0.0111	0.0196
Profile CD	0.00537	0.00539	0.00559	0.00573	0.00586
Total CD	0.00537	0.00663	0.0105	0.0168	0.0255
Cl/CD	0.00	14.44	18.19	17.08	14.99
CM	0.00	-0.119	-0.237	-0.355	-0.473
Roll Coefficient	0.00	0.107	0.213	0.318	0.421
Yaw Coefficient	0.00	0.00	0.00	0.00	0.00
Pitch Moment/Lift (in)	No Lift	48.76	48.77	48.78	48.79
Roll Moment/Lift (in)	No Lift	-43.84	-43.76	-43.62	-43.44
Yaw Moment/SideForce (in)	No Side Force	No Side Force	No Side Force	No Side Force	No Side Force
Speed (knots)	10.00	10.00	10.00	10.00	10.00
Angle of Attack	0	2	4	6	8
Power Usage (hp)	2.76	3.41	5.41	8.63	13.09

Figure 18: Results for 30 degrees sweep angle.

Results Summary

	Angle = 0 Deg	Angle = 2 Deg	Angle = 4 Deg	Angle = 6 Deg	Angle = 8 Deg
Total Lift (Pounds)	0.00	1,500.20	2,998.58	4,493.30	5,982.54
Total Side Force (Pounds)	0.00	0.00	0.00	0.00	0.00
Total Drag (Pounds)	89.93	109.57	166.36	259.28	389.03
Body Lift (Pounds)	0.00	0.00	0.00	0.00	0.00
Body Side Force (Pounds)	0.00	0.00	0.00	0.00	0.00
Body Drag (Pounds)	0.00	0.00	0.00	0.00	0.00
Moment (Pound-ft, CG)	0.00	-8665.3514	-17315.0664	-25933.3911	-34504.3381
Roll Moment (Pound-ft, CG)	0.00	5,579.81	11,132.44	16,630.83	22,048.19
Yaw Moment (Pound-ft, CG)	0.00	0.00	0.00	0.00	0.00
Lift Coeff.	0.00	0.0895	0.179	0.268	0.357
Side Force Coeff.	0.00	0.00	0.00	0.00	0.00
Induced CD	0.00	0.00109	0.00436	0.00979	0.0174
Profile CD	0.00537	0.00545	0.00557	0.00569	0.00587
Total CD	0.00537	0.00654	0.00993	0.0155	0.0232
Cl/CD	0.00	13.69	18.03	17.33	15.38
CM	0.00	-0.158	-0.315	-0.472	-0.628
Roll Coefficient	0.00	0.102	0.203	0.303	0.401
Yaw Coefficient	0.00	0.00	0.00	0.00	0.00
Pitch Moment/Lift (in)	No Lift	69.31	69.29	69.26	69.21
Roll Moment/Lift (in)	No Lift	-44.63	-44.55	-44.42	-44.23
Yaw Moment/SideForce (in)	No Side Force	No Side Force	No Side Force	No Side Force	No Side Force
Speed (knots)	10.00	10.00	10.00	10.00	10.00
Angle of Attack	0	2	4	6	8
Power Usage (hp)	2.76	3.36	5.10	7.96	11.94

Figure 19: Results for 45 degrees sweep angle.

The results for 45 degrees sweep angle places the center of lateral resistance at 69 inches from the root leading edge and 44 inches in depth as shown in Figure 19.

For more information about 3DFoil, please visit http://www.hanleyinnovations.com. For availability and price, please call us at (352) 687-4466.