

# HYPERSONIC GLIDER FOR A WAVE-RIDER VEHICLE

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## Abstract

It is in the interest of NASA to investigate if a deployable glider can be utilized for a six-foot hypersonic wave-rider vehicle. This glider should function to stabilize the vehicle when the vehicle decelerates to transonic and subsonic speeds. The design specifications require the glider to be seventy-five percent of the vehicle's length and that the glider is stowed during the hypersonic regime. The design of the glider was inspired from the research done by R.T. Jones of NASA Ames who has shown that oblique wings promise more aerodynamic efficiency for aircrafts flying at transonic and low supersonic speeds (known as the wing sweep theory). From this theory, a prototype of an oblique glider was modeled in Inventor 2008 Professional along with a scaled model of the six-foot wave-rider. It was assembled and placed in a tube at varying angles of attack and sweep. The model was imported into CFDesign where fluid analysis was done to analyze the forces on the wing. The analysis was set for atmospheric conditions at 50 km and local Mach number of 1.2.

The CFD analysis illustrated that the optimal angle of attack was between five and ten degrees. Therefore the analysis was run for angles of attack from five to ten degrees in one degree increments for all the sweep angles. The analysis also showed that the vehicle stalls when it reaches an angle of attack of thirty-five degrees. The pressure distribution from CFDesign analysis showed that the glider can handle the forces the glider experiences. A limitation for this analysis is that it does not account for thermal effects and stresses that the glider experiences when it is stowed.

## Background

In 1998 a series of eleven deployable re-entry bodies were launched from a sounding vehicle at White Sands Missile Range, New Mexico. This project was named SOAREx I (Sub-Orbital Aerodynamic Re-entry Experiment). The nosecone experiment, Slotted Compression RAMP probe (a.k.a. S.C.R.A.M.P), and the Waverider Vehicle (WRV) are the three primary vehicle types. The Waverider Vehicle is currently being

developed at NASA Wallops Flight Facility Goddard Space Flight Center located on the Eastern Shore of Virginia. The Waverider is being designed, manufactured, tested, and launched at NASA Wallops.

There are two Waverider Vehicle designs, one is a four-foot vehicle and the other is a six-foot vehicle. Both vehicles are to test high lift over drag test articles. Their function is to aid in the development of a control system on future planetary entry concept vehicles. They are also to implement aero-braking technology. The four foot vehicle has been successfully launched. The six foot vehicle is still in development.

There are two primary design modifications for the six foot vehicle. There are "flaps" on the bottom of the vehicle to test stability at hypersonic speeds (see Fig. 1). The other is a glider that would deploy at transonic or subsonic speeds. The focus of the glider is to stabilize the vehicle when it approaches transonic speeds. The waverider vehicle is launched at approximately mach six and will decelerate as it falls into Earth from sub-orbit. When the waverider decelerates to transonic speeds, it becomes unstable. Therefore it is the interest of the developers at NASA to investigate if it is possible to install a deployable glider.



Figure 1. Six Foot Wave-rider

## Introduction

Many principles of gas dynamics and fluid mechanics were incorporated for the research. CFDesign performed strictly internal

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flow calculations in order to mesh the fluid area for the purposes of creating differential volumes for analysis. The fluid flow of the glider and the wave-rider is external; however it is assumed that the forces experienced by the glider and waverider in an external fluid flow situation is equivalent to an internal flow situation with the glider and wave-rider functioning as an obstacle.

The glider is to deploy as it first enters the stratosphere which begins at 50 km. The stratosphere is dynamically stable and has horizontal flow characteristics. The conditions that the wave-rider experiences in the stratosphere can be more accurately modeled and parameterized for CFD analysis than at other atmospheric layers.

An elliptical glider was designed in Inventor 2008 according to specification and assembled to a full-scale mock-up of the wave-rider. The assembly was placed in a large tube so that the surface conditions on the tube would not affect the fluid flow conditions around the wave-rider assembly. The whole set-up was loaded into CFD design where the boundary and fluid conditions were applied. Much iteration was run for the assembly at different angles of attack and sweep angles.

## Six Foot Wave-rider

The first task at Wallops was to create a full scale model of the six-foot wave-rider in Inventor. Measurements of the wave-rider were taken using an inclinometer, a ruler, and vernier caliper. The wave-rider has a four and a half degree incline about a plane of symmetry starting at the copper nose tip. The incline is constant through its six foot length. At four feet eight inches from the tip of the wave-rider is another incline of thirteen degrees subtracted from the wedge. The wedge was designed to compress supersonic air flow underneath its body. It has a pressure transducer at its copper tip. The rest of the body is made of sheet metal.

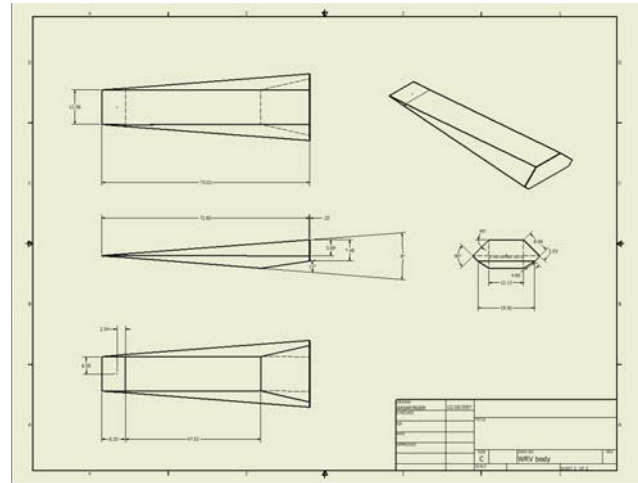


Figure 2. Six-Foot Wave-rider

## Glider

From the material provided in “A Summary of a Half-Century of Oblique Wing Research” (ref. 1) it was decided that the glider should be shaped elliptically. Elliptical wings have great aerodynamic efficiency for transonic and subsonic speeds. These are the speeds in which the wave-rider becomes unstable and the glider is to deploy to stabilize the vehicle. Part of the design criterion is that the glider should be seventy-five percent of the vehicle length. The glider must also be stowed during the initial phases. Therefore the span of the glider is fifty-four inches and has a twelve inch cord. The thickness of the glider is a quarter of an inch.

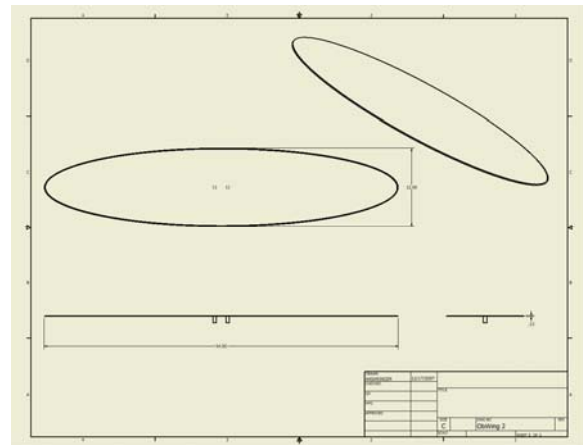


Figure 3. Glider Prototype

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## Setup

The body and the wing were assembled inside a tube with a radius and length of 5000 inches (416.67 ft.). This was the maximum length and radius allowed in CFDesign before it starting reporting meshing errors. From conservation of mass, momentum, and energy the following equation can be derived:

$$\frac{dA}{A} = (M^2 - 1) \frac{dV}{V} \quad \text{equation (1)}$$

The tube has no differential area change; therefore the left-hand side of the equation is equal to zero. The Mach number for the analysis is  $M=1.2$  so the only way for the right-hand side of the equation to be zero is if the differential volume is zero. This ensures that the Mach number approaching the wave-rider is  $M=1.2$ . This tube was necessary for implementing CFDesign which needs an enclosed volume for fluid flow calculations.

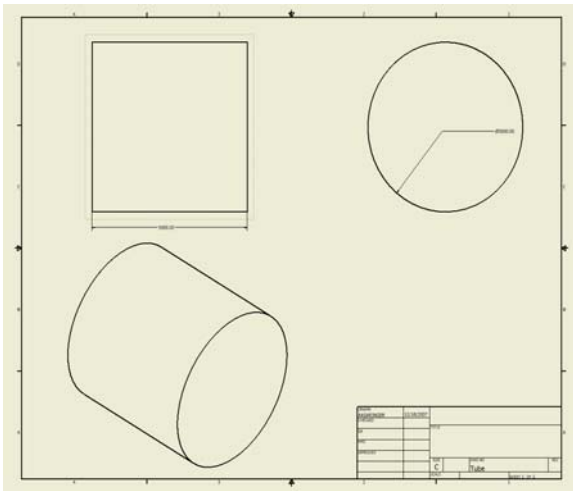


Figure 4. Tube

## CFDesign Procedure

CFDesign is software created by Blue Ridge Numerics Inc. and is the software that was used for the analysis. The following are the steps for the analysis.

1. Pull up the model in Inventor
2. Go to Tools>>Launch CFD **\*Install CFDesign before installing Inventor or this option is unavailable.**

3. On the top left feature tree>>Length Units: hit inch-Watt right click>>change units only

On the bottom left is a feature box with icons.

The trick is to go down the line of icons from top to bottom.

4. Under Boundary Conditions Icon
  - a) Select inlet and put in the value for velocity with proper units ( $V=398$  m/s).
  - b) Hit Apply
  - c) Select inlet and put in the value for temperature ( $T=270.56$  K)
  - d) Hit Apply
  - e) Select inlet and put in the value for pressure ( $P=0.0759$  kPa; absolute)
  - f) Change default to "absolute"
  - g) Hit Apply
  - h) Select side of tube and select "slip/symmetry" from the drop box
  - i) Hit Apply
  - j) Select the outlet and click on "unknown" from the drop box
  - k) Hit Apply
5. Under Mesh Icon
  - a) Go to the Diagnostics Tab
  - b) Click on Parts
  - c) Select all
  - d) Deselect the tube
  - e) Suppress Selected Part(s)
  - f) Go to Automatics Tab
  - g) Apply Automatic Size
6. Under Materials Icon
  - a) Select the vehicle
  - b) For Type >> Solid
  - c) Name >>Aluminum\_Constant
  - d) Select the tube
  - e) For Type >> Fluid
  - f) Before going to Name click on Create/Edit Material...
  - g) In the window change name to Air\_Compressible
  - h) Click on density and on the top right drop box choose "Equation of State"
  - i) Hit Apply
  - j) Change the rest of the values (similar to steps h and i)...  
Viscosity =  $1.703e-05$  Pa-s

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Conductivity = 4.11001e-06  
BTU/ft-s-R  
Specific Heat = 7.71567  
BTU/slu-R  
Compressibility = Cp/Cv 1.4  
Emissivity = 0  
Wall Roughness = 0 inch

- k) In the same window change Reference Properties to Gas Constant = 444852 in<sup>2</sup>/s<sup>2</sup>-K  
Pressure = 0.026053 psi  
Temperature = -109.642 Celsius
  - l) Click OK
  - m) Select the tube
  - n) Type >> Fluid
  - o) Name >> \*Air\_Compressible
  - p) Click Apply
7. Under Select Analysis Type & Options Icon
- a) Make sure Flow>>On
  - b) Compressibility >> Compressible
  - c) Total Temperature >> 346.21 K
  - d) Heat Transfer >> Off
8. Go to the Analysis Icon and due as much iteration as necessary for the graphs to converge.

The analysis for zero wing sweep and various angles of attach were put into project files so that the boundary conditions and mesh sizes could be imported. The instructions to create a project file are in the CFDesign Training Manual. Using the results branch in the feature tree, the scalar results are visually shown for the all of the analysis in the branch.

## Analysis

As the angle of attack increases from zero to thirty degrees the pressure nearly doubles at certain locations of the vehicle and the glider. Even so the pressure is less than 8.3 psf. and can be easily withstood by a quarter of an inch thick stainless steel glider.

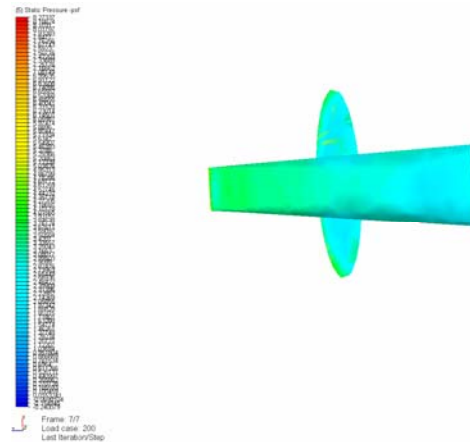


Figure 5. Static Pressure, 0 degrees angle of attack

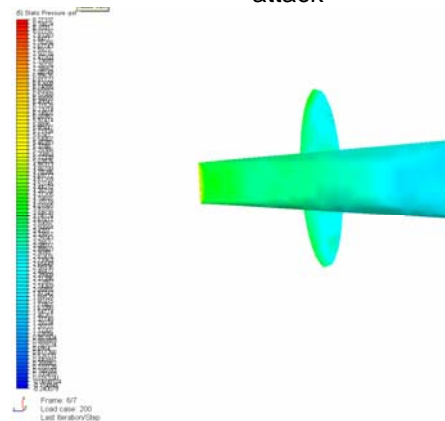


Figure 6. Static Pressure, 5 degrees angle of attack

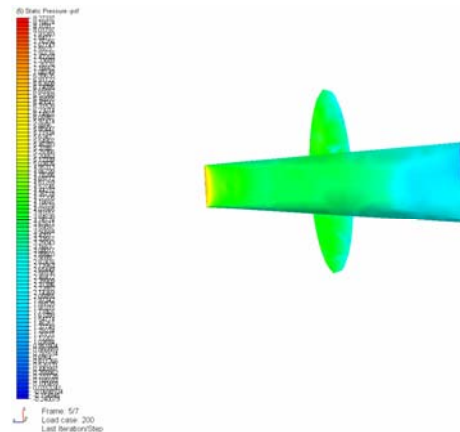


Figure 7. Static Pressure, 10 degrees angle of attack

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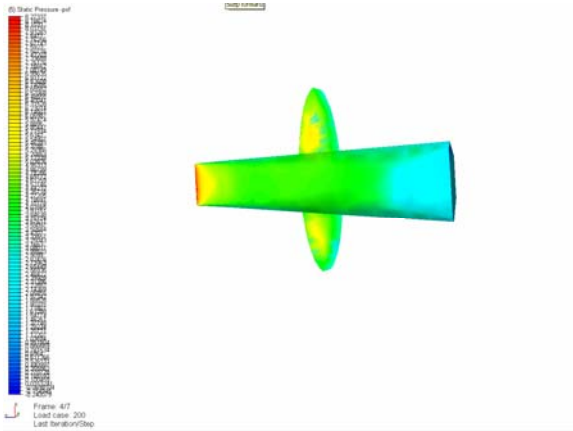


Figure 8. Static Pressure, 15 degrees angle of attack

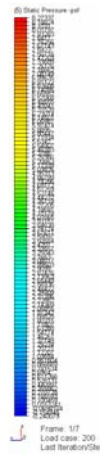


Figure 11. Static Pressure, 30 degrees angle of attack

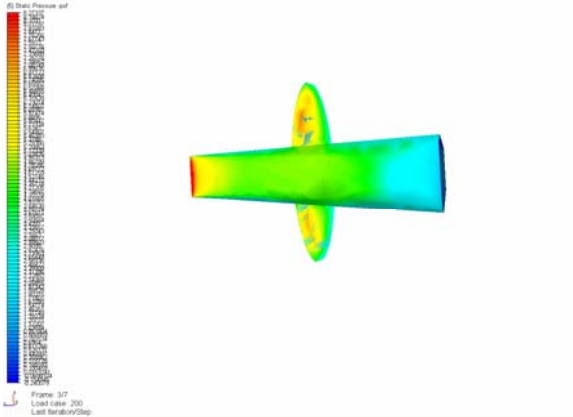


Figure 9. Static Pressure, 20 degrees angle of attack

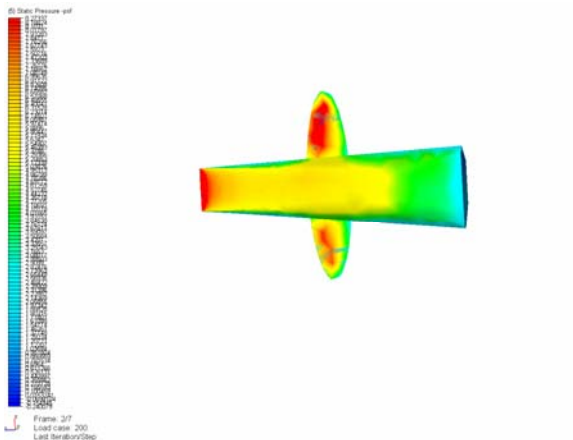


Figure 10. Static Pressure, 25 degrees angle of attack

The fluid velocity profile shows that a shock wave forms around the vehicle. There are oblique shocks following the vehicle. As the angle of attack of the vehicle increases, a compression shock forms on the bottom of the vehicle and an expansion shock forms on the top. The vehicle begins to stall when it reaches an angle of attack greater than thirty degrees

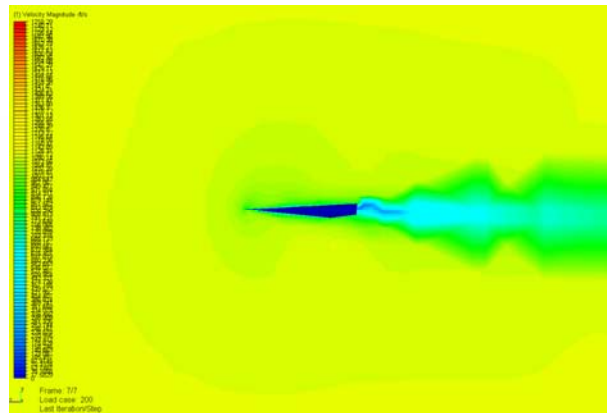


Figure 12. Velocity Magnitude, 0 degrees angle of attack

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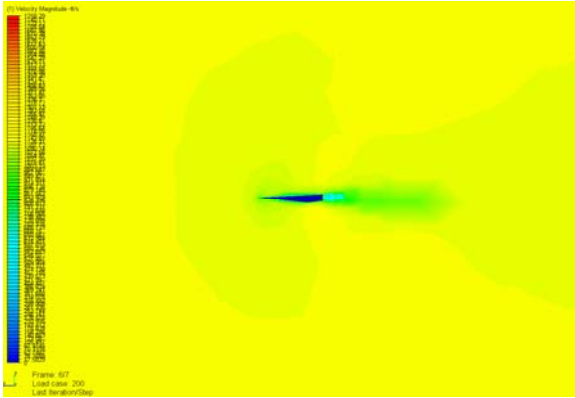


Figure 13. Velocity Magnitude, 5 degrees angle of attack

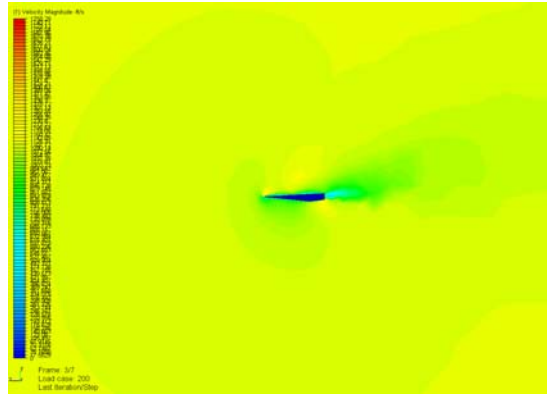


Figure 16. Velocity Magnitude, 20 degrees angle of attack

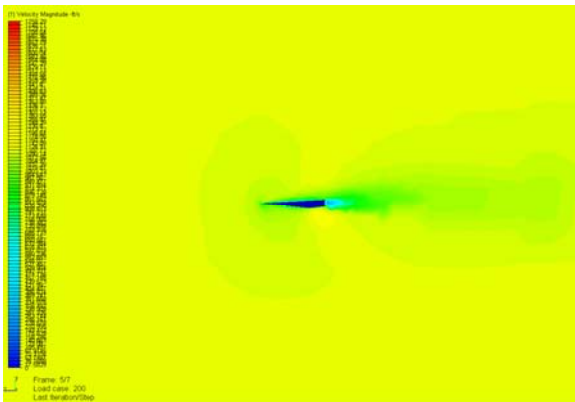


Figure 14. Velocity Magnitude, 10 degrees angle of attack

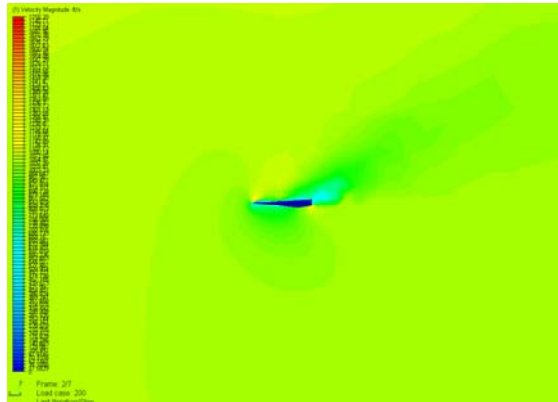


Figure 17. Velocity Magnitude, 25 degrees angle of attack

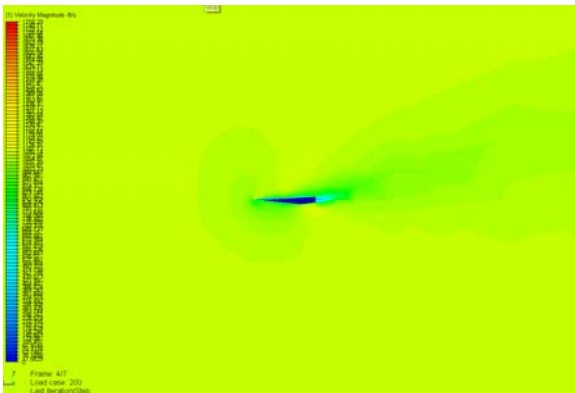


Figure 15. Velocity Magnitude, 15 degrees angle of attack

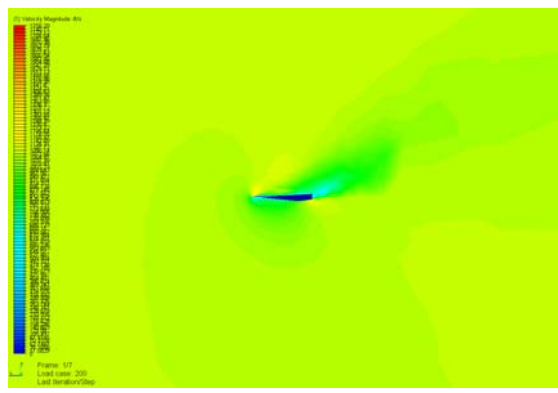


Figure 18. Velocity Magnitude, 30 degrees angle of attack

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A limitation with using CFXDesign is that the fluid volume has to be enclosed and therefore external fluid flow analysis can not be modeled. The way this analysis is setup is that the velocity of the fluid is traveling at approximately mach 1.2 while the vehicle is treated as a stationary obstacle. Therefore velocity magnitude should be reversed. Even so, the pressure distribution on the body of the vehicle and the flow visualization should be equivalent. Another factor that contributes to the equivalency is that the analysis is done for atmospheric conditions at 50 km. This is the starting altitude of the stratosphere which is characterized by horizontal flow. The incoming uniform horizontal flow in the analysis is similar to the type of fluid flow the wave-rider would experience.

The total pressure distribution is nearly symmetrical about the vehicle at zero degrees angle of attack. As the angle of attack increases the total pressure on the bottom increases and the total pressure on the top decreases. The low pressure area on top of the vehicle increases as the angle of attack increases.

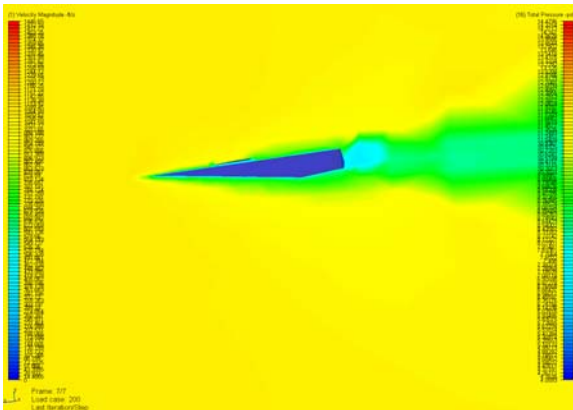


Figure 19. Total Pressure, 0 degrees angle of attack

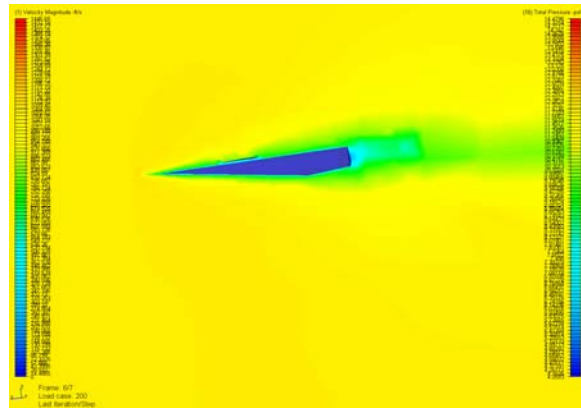


Figure 20. Total Pressure, 5 degrees angle of attack

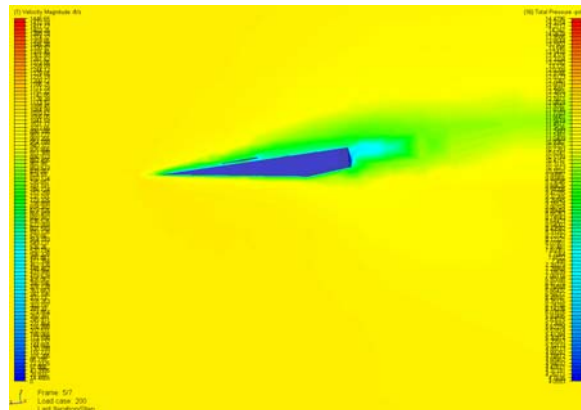


Figure 22. Total Pressure, 15 degrees angle of attack

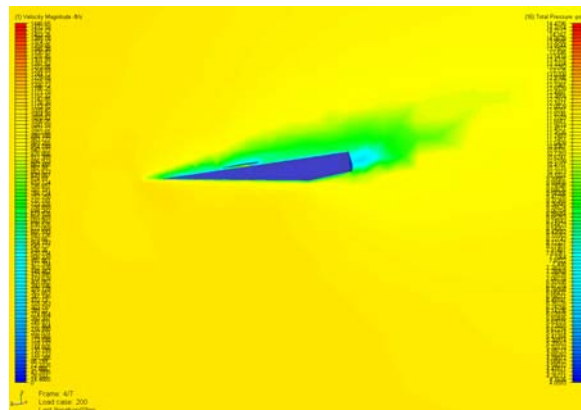


Figure 22. Total Pressure, 15 degrees angle of attack

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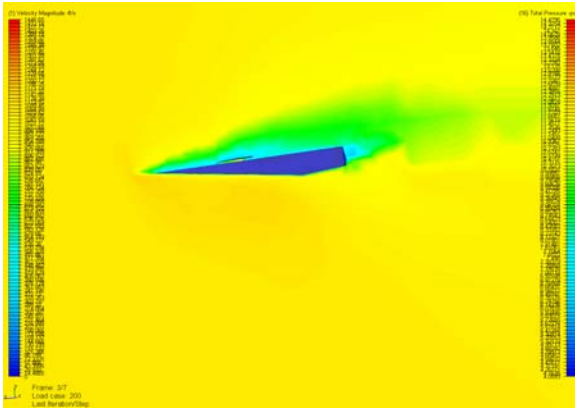


Figure 23. Total Pressure, 20 degrees angle of attack

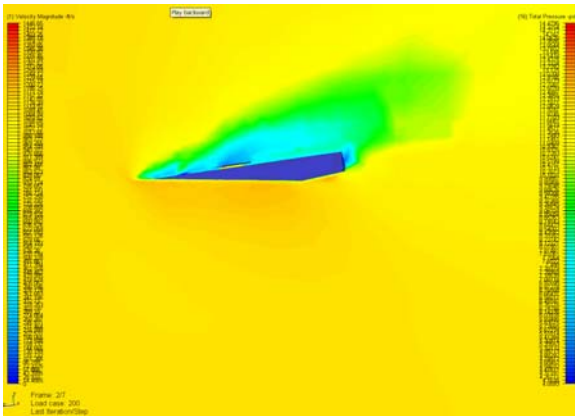


Figure 23. Total Pressure, 25 degrees angle of attack

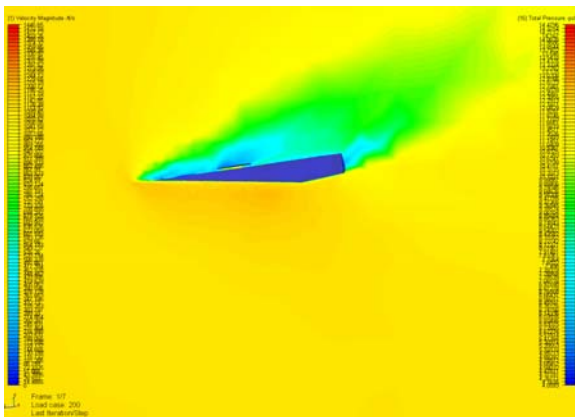


Figure 24. Total Pressure, 30 degrees angle of attack

By 30 degrees angle of attack the difference in pressure distribution on the top and bottom of the vehicle is significant. This pressure difference could help slow down the vehicle. Also flow separation becomes prominent.

## ANSYS

The second analysis stage of my research is to determine what kind of deflections and deformations would occur to the glider. This is to be done by exporting the mesh and results from CFDDesign into ANSYS. The procedure to do this is not completed. The following steps are what I have gathered. Steps 1 through 4 and 10 is done in ANSYS and steps 5 through 9 are done in CFDDesign.

1. Prepare the ANSYS geometry (pull up the model from Inventor). Make sure the model geometry is in the same position and orientation as the CFDDesign analysis model.
2. Build a dummy mesh for the structural analysis.
3. Apply dummy pressures to the appropriate locations in the ANSYS model.
4. Export an analysis deck of file type .ans (or .cdb).

This functionality is found in the traditional ANSYS interface, not the workbench environment interface. Assuming the model is meshed in simulation with the appropriate structural boundary conditions and structural analysis type defined (insert a static structural analysis), highlight the solution branch, then go to the Tools menu and choose "write ANSYS input file". Provide a file name. Shut down workbench, then go to start...programs... ANSYS 11... ANSYS Product Launcher. From the resulting window, specify a working directory (C:\Documents and Settings\aaaringer) preferably where the input file was saved out of workbench. Choose a Job Name (WRV Analysis), and click the Run button at the bottom. That should open Traditional ANSYS. Once ANSYS is open, go to File menu and

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choose “read input from”, and locate the input file written from workbench. The model should be plotted in ANSYS. If not, go to Plot menu...elements.

Next, on the left hand menus, go to preprocessor...archive model...write. On the resulting window, choose the COMB option under “data to archive” and specify a file name under the “archive file” dialog. It should default to the job name.cdb. Just above that there should be an option for ANSYS neutral file. This would be used for the .ans (or .anf) approach as referred to by CFDesign chapter 12. The .cdb approach should suffice. If more instructions are needed contact Matt Mallett at 1-240-547-1099.

5. In the completed CFDesign analysis, go to the Transfer task icon (the last icon).
6. Select the ANSYS deck using the Browse button.
7. Select the Results type to Map (pressure).
8. Indicate if the direction of the pressure should be reversed.
9. Hit the Map Results to BC Button
10. A new deck will be written with results interpolated to the appropriate boundaries. This deck will have the words “\_new BC” appended to the original name. Return to ANSYS, and import the new deck. The boundary condition values will be the result values from CFDesign, and they will be interpolated to the new nodal and/or elemental locations.

These instructions are tentative. I have not been successful. The interface for the ANSYS Workbench that I am using is different from the version that is online.

## Summary

The finite elemental analysis has not been completed. However, I assume that it is plausible for the six-foot wave-rider to have a functioning glider. This assumption is made by looking at the static pressure loads on the bottom of the wing in CFDesign for the wing

sweep of 0 degrees and 30 degree angle of attack. At 30 degree angle of attack the vehicle and the glider experiences the maximum amount of pressure difference for the top and bottom of the glider. At this angle pressure distribution on the glider was not significant (less than 8.3 psf) and would be capable of withstanding the aerodynamic forces resulting from the fluid flow and should not exhibit significant deformation on the glider.

The wave-rider and the glider should experience the maximum amount of forces in this position. In this position, the pressure values were low enough that it should not cause significant deformation on the glider. This analysis does not take into consideration thermal expansion, shock waves, and other stresses the glider might experience prior to reaching 50 km at mach 1.2. As an afterthought, I think it would be great for someone to run more types of analysis that includes thermal/frictional effects.

## References

1. Jones, R.T. “Thin Oblique Airfoils at Supersonic Speed,” Rep. no. 851, Nat. Advis. Comm. for Aeron. (NACA), 1946.  
([http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930091095\\_1993091095.pdf](http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930091095_1993091095.pdf)).
2. Curry, Robert E., and Sim Alex G., “In-Flight Total Forces, Moments, and Static Aeroelastic Characteristics of an Oblique-Wing Research Airplane,” NASA Technical Paper 2224, October 1984.
3. Hirschberg, Michael J., Hart, David M., and Beutner, Thomas J., “A Summary Of A Half-Century of Oblique Wing Research,” 45th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2007-150, Jan. 2007.