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Wind Tunnel Study of a Large Aerostat, CFD Validation

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To further the development of larger and more capable aerostats at TCOM, an update to the aerodynamic database was needed. This led to comprehensive wind tunnel testing conducted in the Glenn L. Martin (GLM) Wind Tunnel at the University of Maryland in 2010. The setup and results of this wind tunnel test were documented in Ref. 1. As part of the continuous validation process, the results of the GLM 2010 wind tunnel test were used to validate the Computational Fluid Dynamics (CFD) method used at TCOM. The validation includes matching the force and moment coefficients and the pressure distributions from the GLM 2010 test.

Nomenclature

α	=	angle of attack, Alpha in degrees
β	=	angle of sideslip, Beta in degrees
ψ	=	angle of yaw, Psi in degrees = $-\beta$
C_D	=	drag force coefficient
C_L	=	lift force coefficient
C_m	=	pitching moment coefficient
C_n	=	yawing moment coefficient
C_p	=	pressure coefficient
C_S	=	side force coefficient
CFD	=	computational fluid dynamics
c	=	reference length, length of the hull
FEM	=	finite element model
GLM	=	Glenn L. Martin (wind tunnel)
S	=	hull reference area = $V^{2/3}$
V	=	hull volume
V_∞	=	freestream velocity

I. Introduction

As discussed in Ref. 1, technological innovations have allowed for economically feasible designs of larger lighter than air vehicles. Larger vehicles, which are defined as in excess of 2,000,000 ft^3, allow for heavier payloads at higher altitudes. In support of these larger designs, the importance of accurate aerodynamic data is critical to define design requirements and fully characterize the aerodynamic behavior. With the larger designs that can withstand approximately 100 knot wind environments, the historic wind tunnel database was nearly two orders of magnitude lower in Reynolds number than actual flight conditions.

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As discussed in Ref. 1, the Reynolds number has a significant effect on drag and therefore an update to the aerodynamic database was needed. This established the requirement for a wind tunnel test at higher speeds and a larger model than had previously been used, bringing the experimental results to approximately one order of magnitude lower in Reynolds number than actual flight conditions. This experimental data was documented in Ref. 1 which compared favorably to the the historical aerodynamics and methods for similar, but smaller aerostat and airship shapes in Ref. 2 to 7. The CFD method was validated by running at the 2010 test conditions, which had favorable comparisons to the force and moment coefficients and the pressure distributions for both Alpha and Beta sweeps. Then the validated CFD method could be applied to the operating aerostats. These operating aerostats would have effects that the wind tunnel would not be able to represent, such as the Reynolds number effects of full-scale aerostats (with up to ~120 m hull chord lengths).

Fig. 1 shows a visual representation of the progression of Reynolds number improvement. The GLM wind tunnel data allowed an order of magnitude improvement in Reynolds number scaling over the historical (before 2010) sub scale tests. Once the CFD method was validated at the 2010 test Reynolds numbers, the CFD method was run at the full-scale operating aerostats Reynolds numbers and therefore would not require scaling. In addition, small configuration changes from the 2010 wind tunnel model to the operating aerostat could be analyzed with validated CFD. Note that the sub scale facilities in Fig. 1 are as follows:

1) NSWC is the Naval Surface Warfare Center Wind Tunnel of the Carderock Division in Maryland
2) Davidson is the Davidson Rotating Arm Water Tank at the Stevens Institute of Technology in New Jersey
3) UT is the University of Toronto Institute for Aerospace Studies Wind Tunnel in Ontario
4) GLM is the Glenn L. Martin Wind Tunnel in Maryland discussed in Ref. 1.

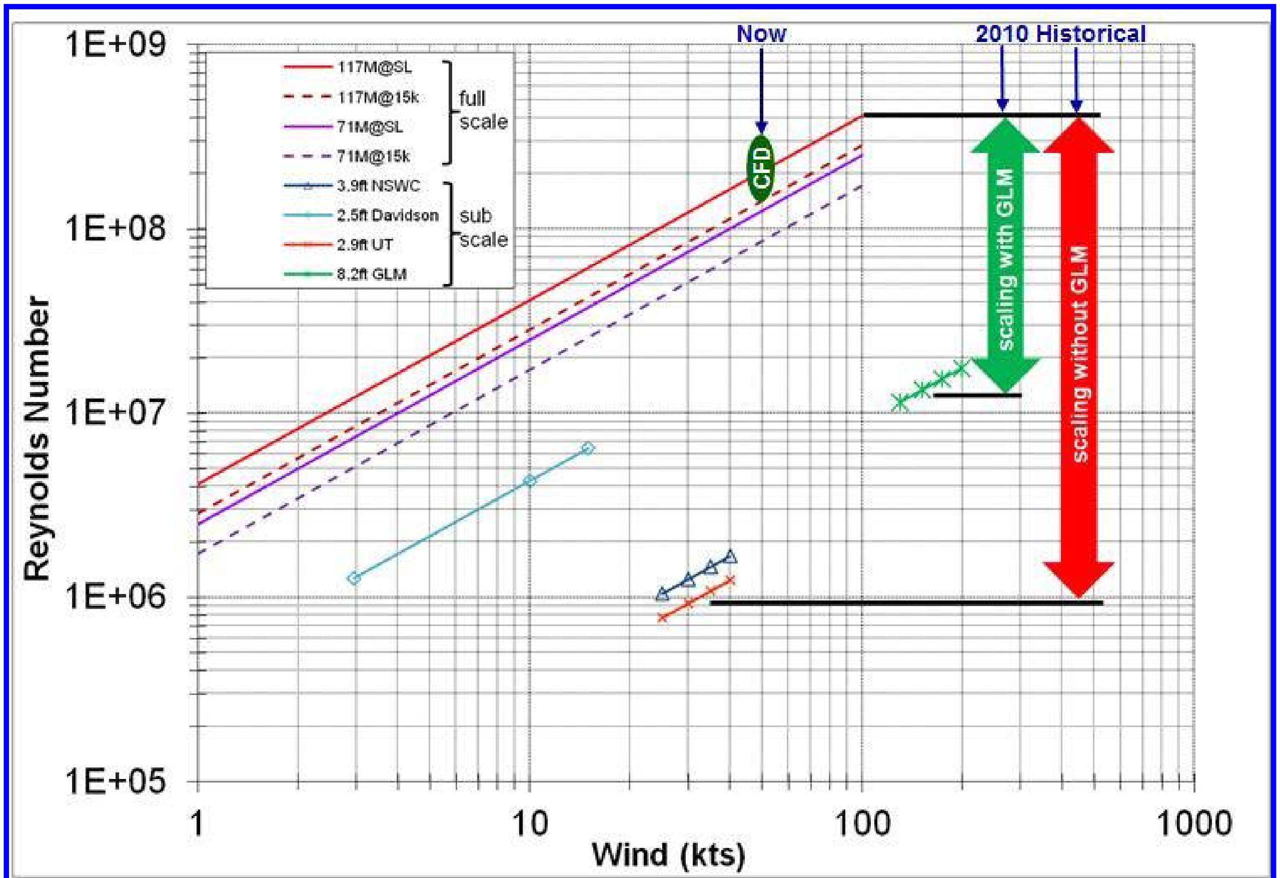


Figure 1. Reynolds number comparison between full scale and sub scale.

The update of the aerodynamic database will continue to build upon and validate historical analysis tools, in particular for the larger aerostats. The TCOM historical analysis tools include:

1) TCOM's static aerostat performance program named FLIGHT
2) TCOM's 6-degree-of-freedom, Non-Linear Dynamic Simulation program named NLDS
3) With the validated CFD method, the interpolation of the pressure distribution on to the FEM is no longer from the relatively course grid of test data pressure taps, but instead from a much more detailed CFD mesh (CFD mesh is more detailed than that required for the FEM).

II. Setup of the CFD

The CFD method used a commercially available CFD solver. The CFD boundary conditions are shown in Fig. 2. As noted on Fig. 2, symmetry was used to reduce the computation time for the Alpha sweeps. The CFD boundary conditions were set to match the nominal conditions of the wind tunnel test:

1) Freestream velocity, V_∞ = 153.3 mph
2) Ambient temperature, T_∞ = 78.4°F
3) Ambient pressure, P_∞ = 14.58 psi
4) Density, ρ = 0.002263 slugs/ft^3
5) Subscale model hull chord, c = 8.2 ft
6) Test section dimensions of 7.75 ft high by 11.04 ft wide

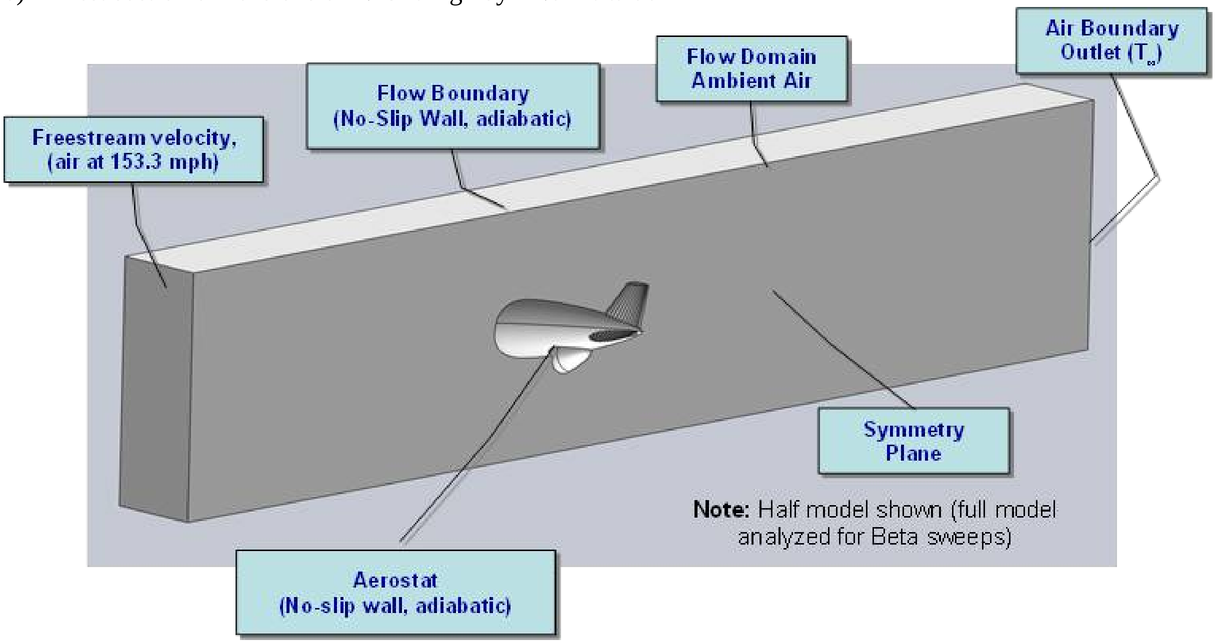


Figure 2. CFD boundary conditions

A sample mesh is shown in Fig. 3, where a detailed boundary layer around the aerostat was used to improve the results, especially in drag. Also, a boundary layer was applied to the wind tunnel walls in order to match any minor effects of the walls at the extreme angles of the sweeps. The mesh size ranged from 16 to 22 million elements for the symmetric Alpha sweeps and 31 to 37 million elements for the Beta sweeps.

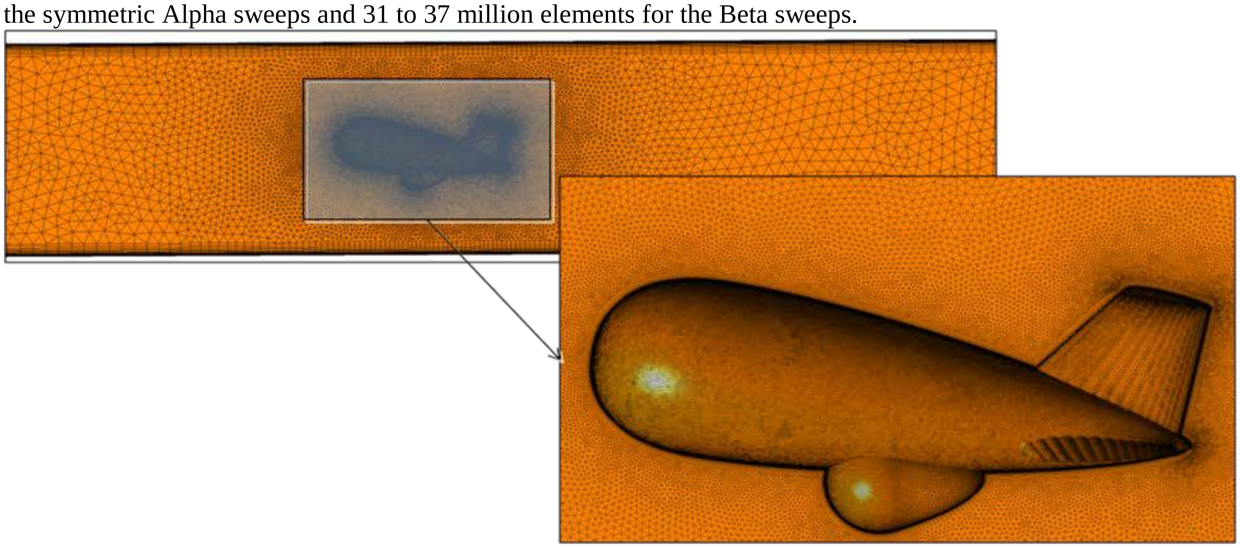


Figure 3. Sample CFD mesh.

III. Comparison of the CFD Results to the 2010 GLM Wind Tunnel

In the following two sections, the wind tunnel test results are detailed which consist of the force and moment data and the pressure distribution data. The two reference parameters for reducing the data are as follows:

1) c = 2.5 m
2) S = 0.77 m^2

Example calculations for the standard aerodynamic coefficients are as follows:

1) C_p = Pressure/(0.5*density*velocity^2*S)
2) C_L = Lift/(0.5*density*velocity^2*S)
3) C_D = Drag/(0.5*density*velocity^2*S)
4) C_m = Pitching_Moment/(0.5*density*velocity^2*S*c), note that all moments are taken about the nose
5) C_n = Yawing_Moment/(0.5*density*velocity^2*S*c), note that all moments are taken about the nose.

Also note that all of the data is for the 2010 GLM wind tunnel test at the baseline speed of 150 mph and for the current configuration of the large aerostat for which this analysis was performed (lower fins at low anhedral angle as discussed in Ref. 1).

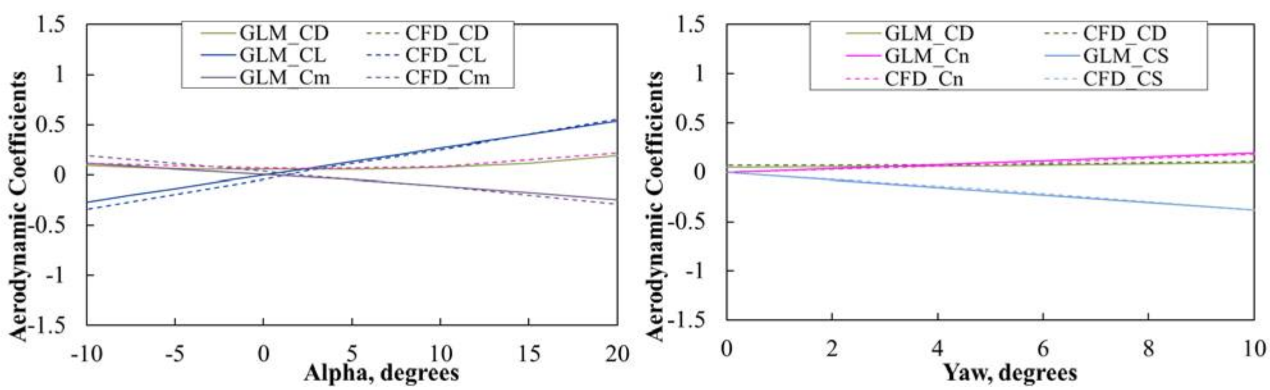
A. Force and Moment Data

The CFD results compare favorably with the 2010 GLM wind tunnel test. Fig. 4 shows the force and moment coefficients vs. the 2 main angle sweeps of Alpha and Yaw in degrees. Therefore, the effect of each parameter should be seen by examining the set of Alpha and Yaw sweeps which is the reason that Fig. 4 is numbered as an a) and b) set to be consistent with Ref. 1:

a) Alpha (α):
   1. C_D = drag force coefficient
   2. C_L = lift force coefficient
   3. C_m = pitching moment coefficient

b) Yaw (ψ):
   1. C_D = drag force coefficient
   2. C_S = side force coefficient
   3. C_n = yawing moment coefficient

Fig. 4 show the comparison of the GLM (solid lines) and CFD (dotted lines). As seen in these figures, the trends of the data are similar.



a) Alpha Sweep **b) Yaw Sweep**

Figure 4. Force and Moment Data.

B. Pressure Distribution

Pressure distribution comparisons between the CFD and the 2010 GLM test are discussed below. As seen in Fig. 5, the 2010 wind tunnel test 80 pressure taps were primarily placed at the four 90 degree circumferential quadrants to obtain comprehensive pressure distributions. This view is correct for pitch angle sweeps at zero yaw. For yaw sweeps at zero pitch, the aft section is rotated 90 degrees such that the windscreen is at 0 degrees. Taps were not located in the forward hull at 180^{o} since that data would always be influenced by being directly in front of the strut.

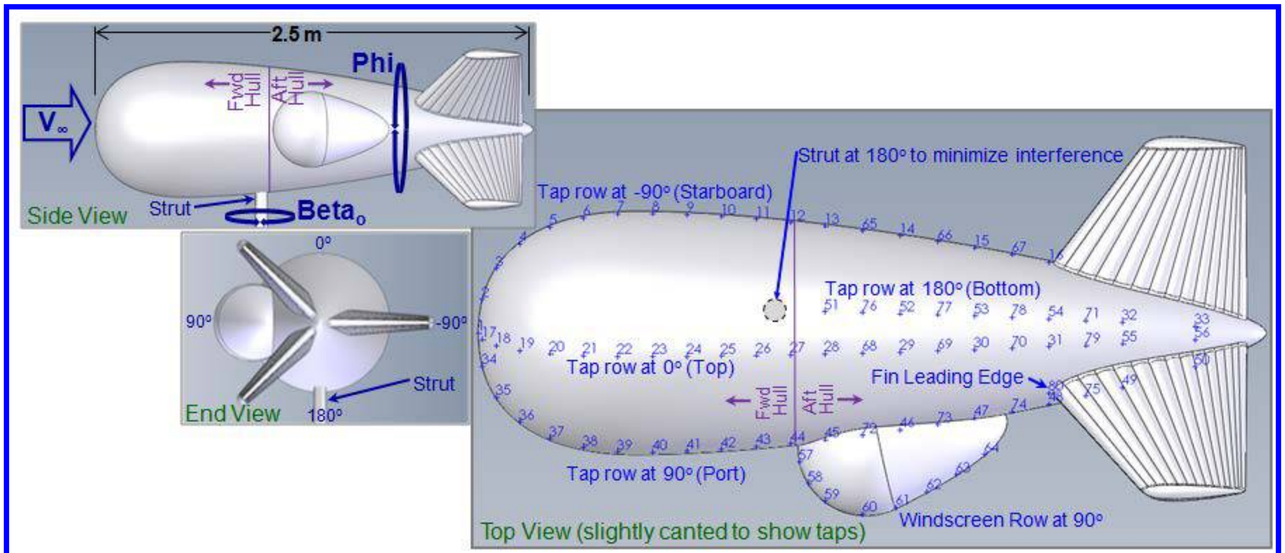


Figure 5. Model pressure tap locations.

Fig. 6 shows a favorable pressure comparison between the CFD and wind tunnel data for zero pitch and zero yaw. The "bow wake" in front of the windscreen shown by CFD was not shown in the wind tunnel data (it occurred between pressure taps). Comparison of pressure data for 10 degrees pitch is shown in Fig. 7. Again, the pressure coefficients from CFD agree well with the wind tunnel pressure data. The 0 and 180 degree lines in CFD are identical for both plots. For the 90 and 270 degree curves, the 90 degree curve is the one with the pressure excursions due to the windscreen.

As expected, if the force and moment data agree, the pressure data must also agree. Pressure obtained from CFD is reasonable to use for structural analysis.

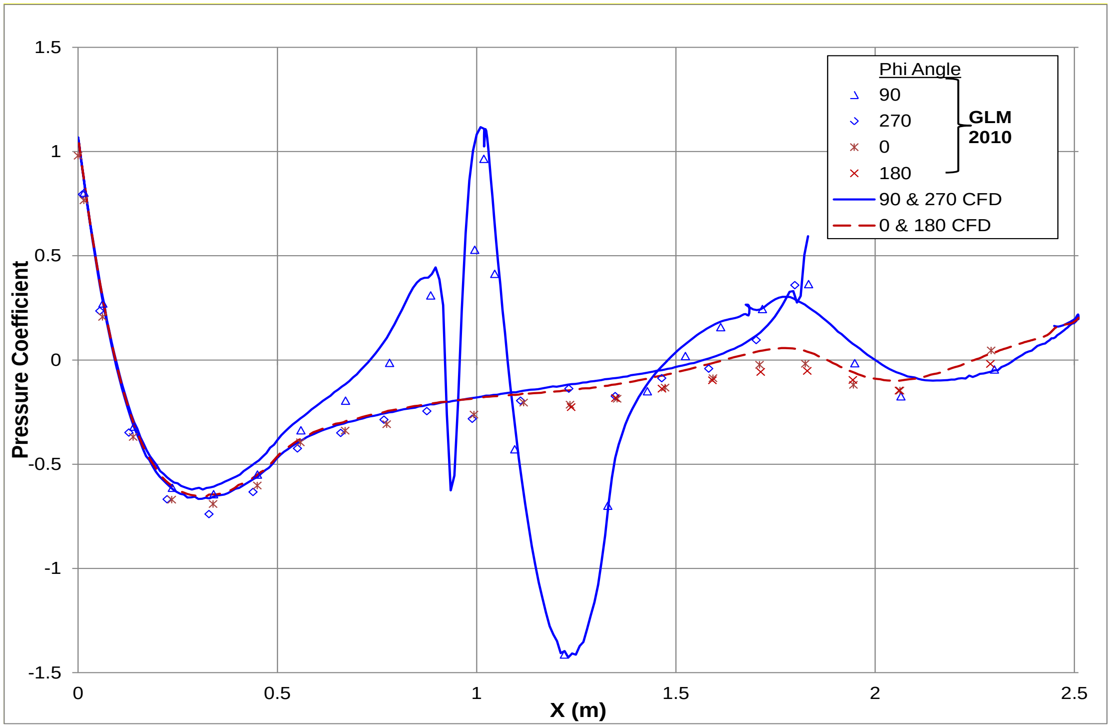


Figure 6 Pressure Comparison for Zero Pitch and Zero Yaw.

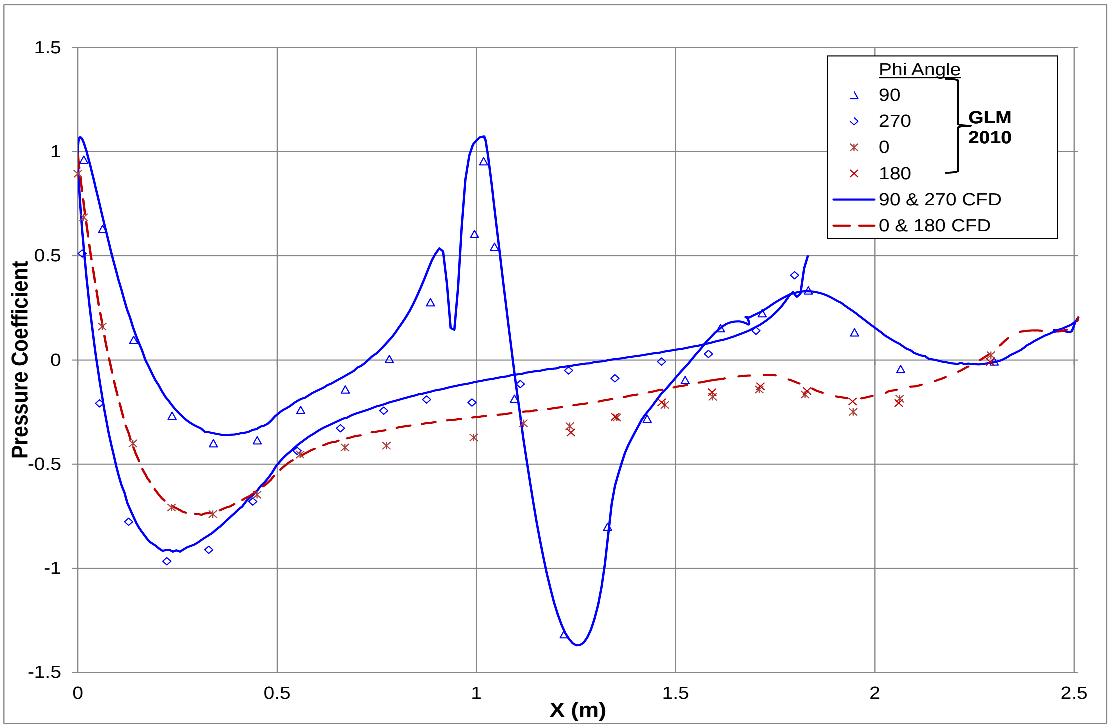


Figure 7 Pressure Comparison for 10 Deg. Pitch and Zero Yaw.

IV. Full Scale Model Analysis

After the CFD method was validated for the wind tunnel scale model at sea level, it was used to find the aerodynamic coefficients and pressure distributions for a full scale model at flight altitude. Additional combinations of pitch and yaw angles were also analyzed to add to the aerodynamic database.

In design of the full scale model, minor changes were made in the fin size, and in the windscreen size and location. With CFD, it is not necessary to go back into the wind tunnel for analysis of models with minor changes in geometry.

V. Conclusion

Since CFD method has been validated against the 2010 GLM force and moment data and pressure distributions, it is a valid set to use in updating the aerodynamic database. The trends are as expected and the Reynolds number drag scaling is further improved by an order of magnitude over historical tests. Also, the pressure distributions show the proper trends and are appropriate to use as inputs to FEM structural analyses on aerostat systems. The reduction of the wind tunnel data for incorporation into the simulation programs FLIGHT and NLDS was done in accordance with the methods in Ref. 8 and 9.

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