

Jig Twist Optimization of Mach 0.8 Transonic Truss-Braced Wing Aircraft

Juntao Xiong*

KBR Wyle, Inc., Moffett Field, CA 94035

Nhan Nguyen[†]

NASA Ames Research Center, Moffett Field, CA 94035

Robert E. Bartels[‡]

NASA Langley Research Center, Hampton, VA 23681

This paper presents a jig twist optimization study of Mach 0.8 Transonic Truss-Braced Wing (TTBW) aircraft using FUN3D. The solver has been validated against wind tunnel test data. An aeroelastic model deformation correction method is developed for the wind tunnel model to improve the validation. The flight condition corresponding to Mach 0.8 and design lift coefficient 0.695 is selected for the TTBW aircraft jig twist optimization to reduce the drag coefficient. The static aeroelastic simulation module in FUN3D is used for the aeroelastic simulation. Three different orders of the Chebyshev polynomials are used as shape function to represent the variations of the jig twist distribution along the wing span. The preliminary optimization results show that the Mach 0.8 TTBW aircraft with the optimized jig twist achieves a drag reduction of about 5.7 counts at the design condition when 5th order Chebyshev polynomials are used as shape function.

I. Introduction

The demand for green aviation is expected to increase with the need for reduced environmental impact of air travel. Most large transports today operate within the best cruise L/D range of 18-20 using the conventional tube-and-wing design. This configuration has led to incremental improvements in aerodynamic efficiency over this past century. In recent years, the use of lightweight materials, such as composites, has been shown to significantly reduce structural weight and trim drag, leading to improved energy efficiency. The Boeing 787 transport is an example of a modern airframe design that employs lightweight structures. High aspect ratio wing design can provide another opportunity for further improvements in energy efficiency.

Research and development of high aspect ratio wing transport designs has placed a greater emphasis on the studies of aeroelasticity and flutter owing to the increase in the wing flexibility as the wing aspect ratio increases. These studies have sought to develop methods and tools for aeroelasticity by laying the foundation for more modern high aspect ratio wing aircraft such as the Transonic Truss-Braced Wing (TTBW). The TTBW aircraft concept is a Boeing-developed N+3 aircraft configuration funded by NASA Aeronautics Research Mission Directorate (ARMD) Advanced Air Transport Technologies (AATT) project.^{1,2,3} The TTBW aircraft concept is designed to be aerodynamically efficient by employing a wing aspect ratio of about 19.55, which is significantly greater than those of cantilever wing transport configurations. Without structural bracing, the increase in the wing root bending moment would require a significant structural reinforcement which would lead to an increase in the structural weight that would offset the aerodynamic benefit of the high aspect ratio wing. Thus, the design of a truss-braced structure is a Multidisciplinary Design Optimization (MDO) process that strives to achieve a delicate balance between aerodynamic efficiency and structural efficiency.

In SUGAR Phase IV, Boeing updated the TTBW concept to operate at a cruise Mach number 0.80 which is consistent with today's commercial transport aircraft.⁴ Figure 1 illustrates the concept of the Mach 0.8 TTBW aircraft. The jig shape geometry of the Mach 0.8 TTBW configuration comes with a pre-twist wing geometry designed for a wind tunnel test. The jig shape OML geometry is not a flight jig shape, which accounts for the wing aeroelastic wash-out twist for the full-scale vehicle at the design flight condition, but is a wind tunnel model jig shape. Thus, the wind tunnel jig shape

*Aerospace Engineer, Intelligent System Division, juntao.xiong@nasa.gov, AIAA Member

[†]Senior Research Scientist and Technical Group Lead, Intelligent Systems Division, nhan.t.nguyen@nasa.gov, Associate Fellow AIAA

[‡]Research Aerospace Engineer, NASA Langley Research Center, MS 340, robert.e.bartels@nasa.gov, AIAA Senior Member

model is suitable for comparisons to wind tunnel data, but not necessarily suitable for generating a full flight dynamics model. In this paper an optimization strategy is developed in order to formulate a flight-optimized jig twist model. The objective is to minimize the drag coefficient of the Mach 0.8 TTBW jig shape geometry by optimizing the jig twist distribution along the wing spanwise direction at the cruise flight condition.



Figure 1 Boeing SUGAR Mach 0.8 Transonic Truss-Braced Wing (TTBW) Aircraft Concept

II. Computational Approach

A. Numerical Code

The computational fluid dynamics code used in this study is FUN3D,^{5,6} which solves the unsteady three-dimensional Navier-Stokes equations on mixed-element grids using a vertices-centered finite-volume method. Information exchange for flow computation on different partitions using multiple CPUs is implemented through the MPI (Message Passing Interface) protocol. It employs an implicit upwind algorithm in which the inviscid fluxes are obtained with a flux-difference-splitting scheme. At interfaces delimiting neighboring control volumes, the inviscid fluxes are computed using an approximate Riemann solver based on the values on either side of the interface. The Roe flux difference splitting⁷ is used in the current study. For second-order accuracy, interface values are obtained by extrapolation of the control volume centroidal values, based on gradients computed at the mesh vertices, using an unweighted least squares technique. The Venkatakrishnan⁸ limiter is used in the current study to limit the reconstructed values when necessary. In this study the tetrahedral mesh with prism layers are used. In FUN3D, for tetrahedral meshes, the full viscous fluxes are discretized using a finite-volume formulation in which the required velocity gradients on the dual faces are computed using the Green-Gauss theorem. The solution at each time-step is updated with a backwards Euler time-differencing scheme. At each time step, the system of equations is approximately solved with either a multi-color point-implicit procedure or an implicit-line relaxation scheme. Local time-step scaling is employed to accelerate convergence to steady-state. To model turbulent flows, the one-equation model of Spalart-Allmaras⁹ (S-A) is used in this study.

The static aeroelastic simulation module in FUN3D is used for the Mach 0.8 TTBW aircraft aeroelastic simulation.^{10,11} The Mach 0.8 TTBW aircraft mode shapes are extracted from Boeing NASTRAN model with 50% fuel. Figure 2 shows the first six mode shapes of the Mach 0.8 TTBW aircraft which are interpolated from the NASTRAN mode shapes. The contour color represents the nodal displacement.

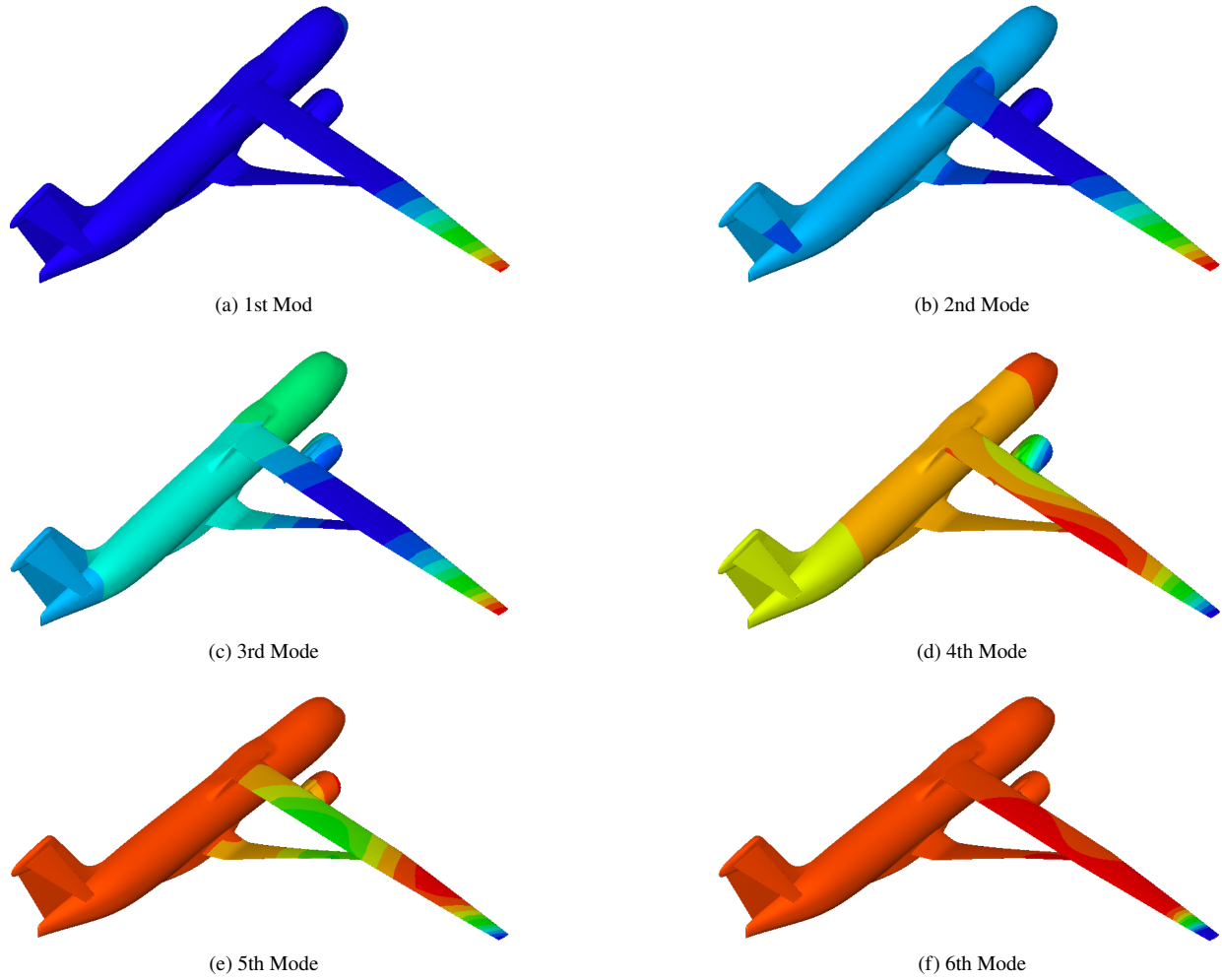


Figure 2 Mach 0.8 TTBW Mode Shapes for 50% Fuel.

B. CFD Solver Validation

Firstly, steady-state simulations for the Mach 0.8 TTBW 1G geometry config-138 at zero tail incidence are conducted at Mach 0.2, 0.8, and 0.92 for comparison to the wind tunnel data¹². The Mach 0.2 wind tunnel data are from the LaRC 14-By-22 wind tunnel test and the high-speed data are from the ARC 11-Ft wind tunnel test. Test data from Run 672 at Mach 0.2 and Reynolds number of 0.96 million, Run 679 at Mach 0.8 and Reynolds number of 1.7 million, and Run 683 at Mach 0.92 and Reynolds number of 1.7 million based on the mean aerodynamic chord (MAC) with full wind tunnel model corrections are available for validation.

Figure 3 illustrates the Mach 0.8 TTBW 1G geometry config-138. Figure 4 shows the CFD mesh. The volume mesh is comprised of tetrahedral elements and a prism layer near the wall. The mesh size is about 98 million nodes. The prism layer is used to resolve the turbulent boundary layer. The y^+ of the first cell from the wall is less than 1.

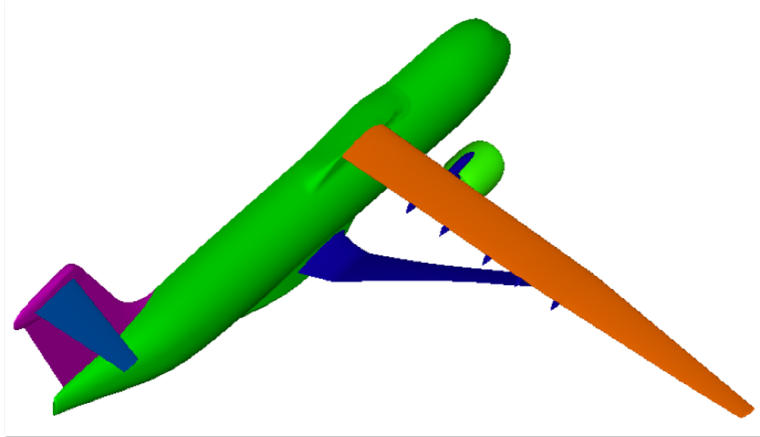


Figure 3 Mach 0.8 TTBW Geometry config-138 Concept

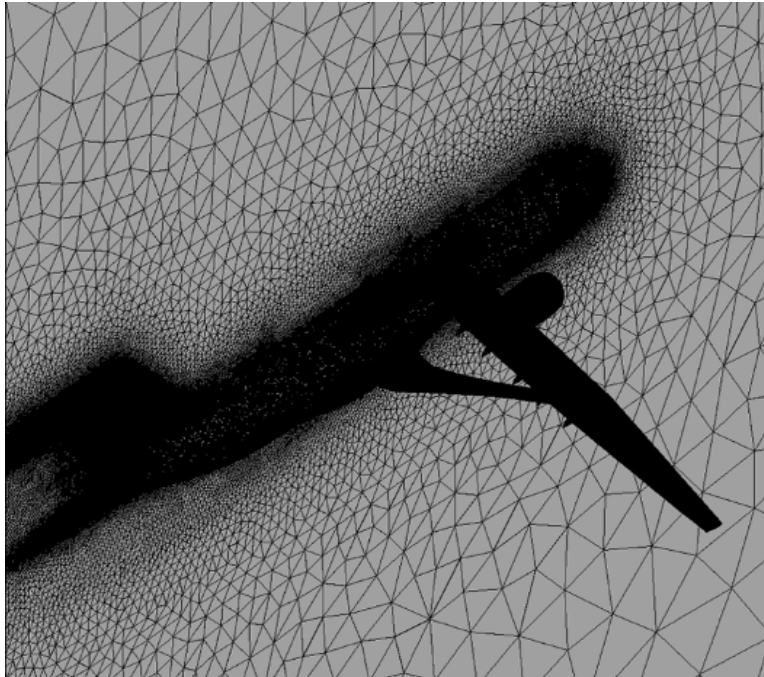
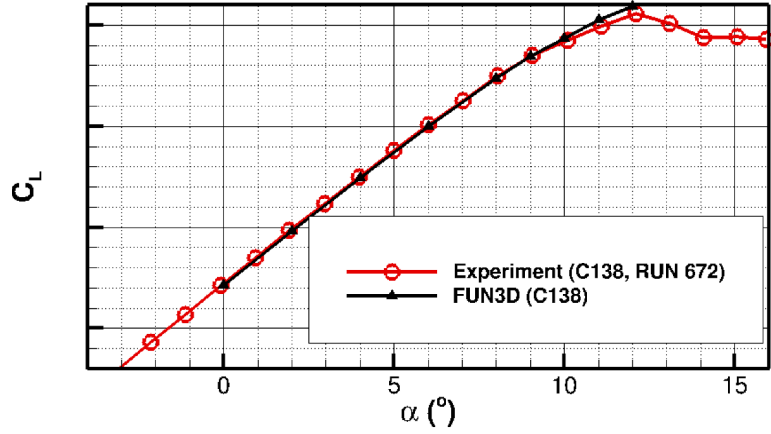
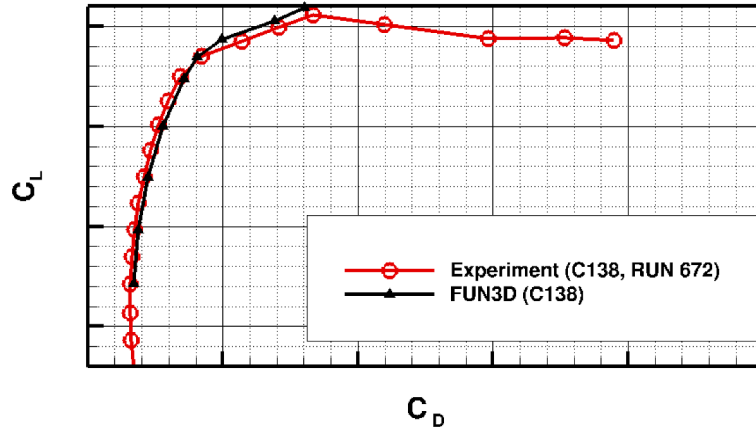


Figure 4 TTBW Aircraft CFD Mesh Concept

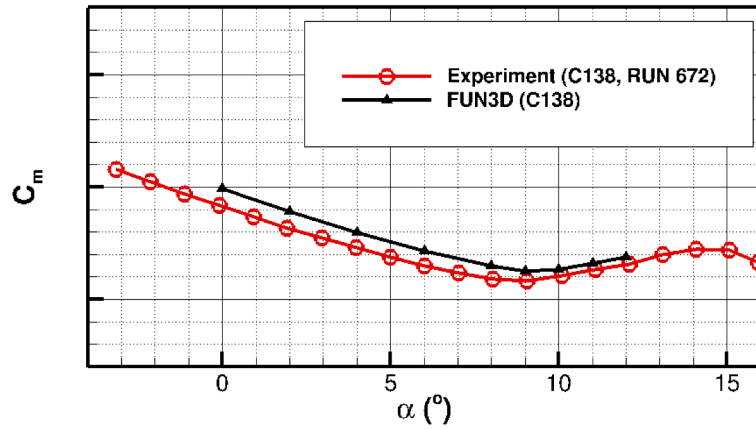
Figure 5 - 7 shows the lift, drag, and pitching moment coefficients of the Mach 0.8 TTBW 1G geometry config-138 computed by FUN3D as well as wind tunnel data for Mach 0.2, 0.8, and 0.92. Compared to the experimental data, FUN3D slightly overpredicts the lift and moment coefficient. This offset may be partially due to the wind tunnel model deformation, which should be further discovered. The drag polar computed by FUN3D shows good agreement with the wind tunnel data. The discrepancy in the drag coefficient progressively becomes larger at larger lift coefficients. Figure 8 - 10 shows the surface pressure coefficient distribution at one simulated flight condition for each Mach number of config-138.



(a) Lift Curve

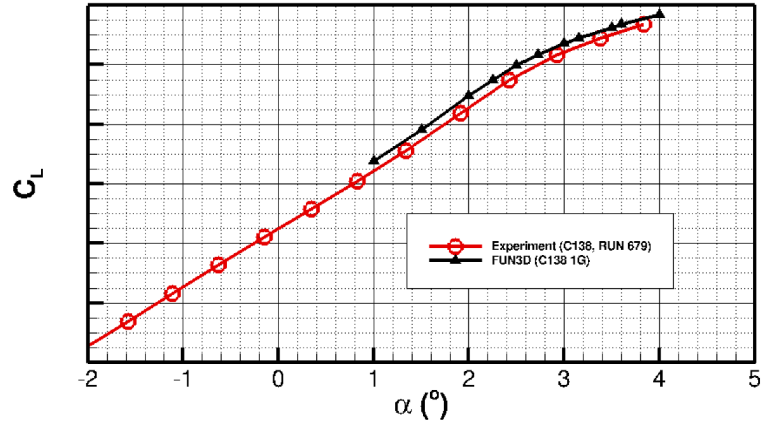


(b) Drag Polar

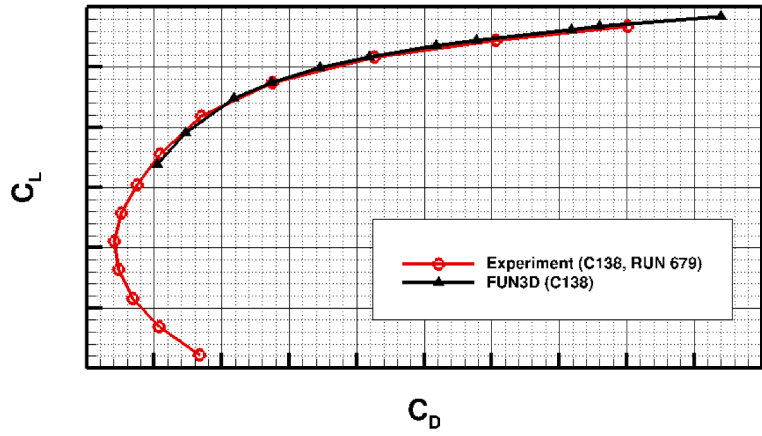


(c) Pitch Moment Curve

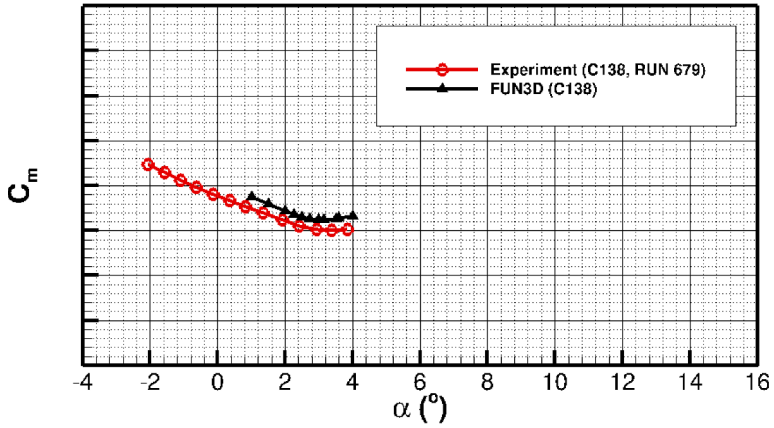
Figure 5 Comparison of Lift, Drag, and Pitching Moment Predictions for the TTBW 1G Geometry Config-138 at Mach 0.2 and $Re = 0.96 \times 10^6$.



(a) Lift Curve

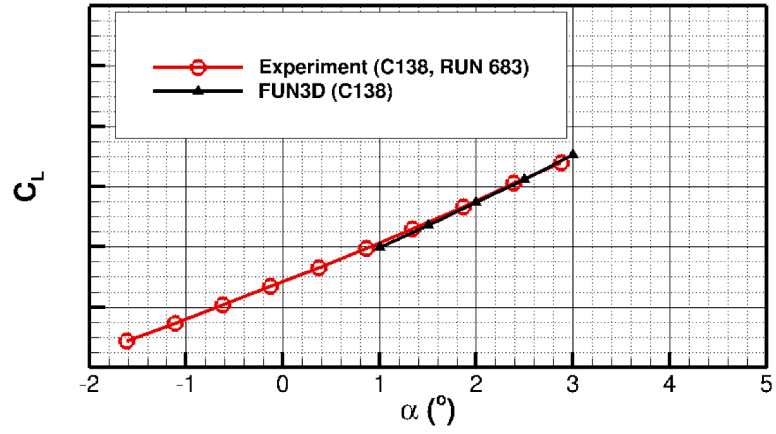


(b) Drag Polar

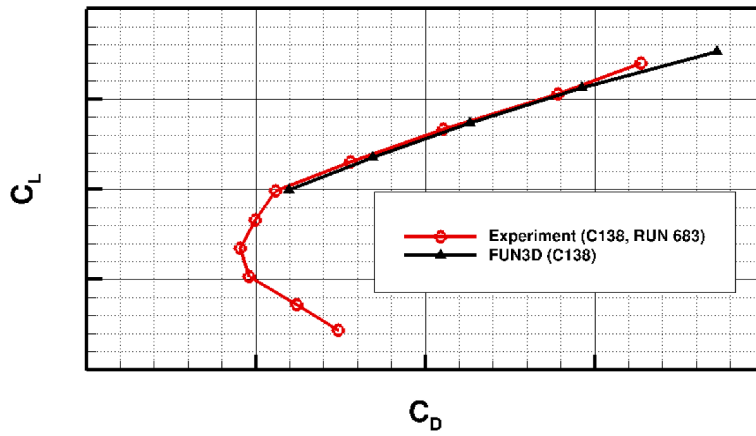


(c) Pitch Moment Curve

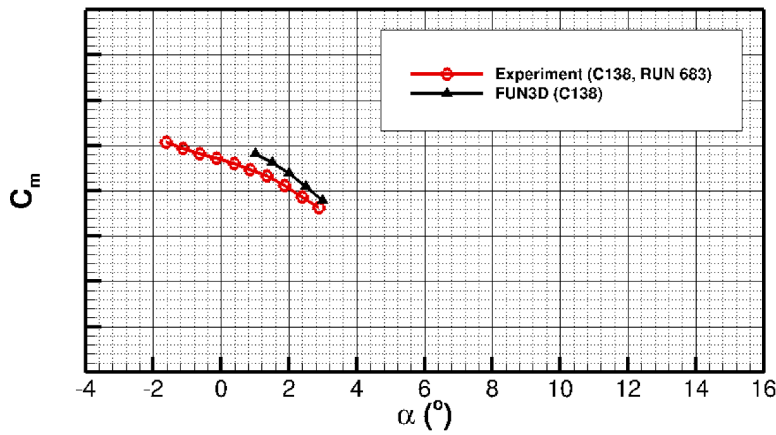
Figure 6 Comparison of Lift, Drag, and Pitching Moment Predictions for the TTBW 1G Geometry Config-138 at Mach 0.8 and $Re = 1.7 \times 10^6$.



(a) Lift Curve



(b) Drag Polar



(c) Pitch Moment Curve

Figure 7 Comparison of Lift, Drag, and Pitching Moment Predictions for the TTBW 1G Geometry Config-138 at Mach 0.92 and $Re = 0.96 \times 10^6$.

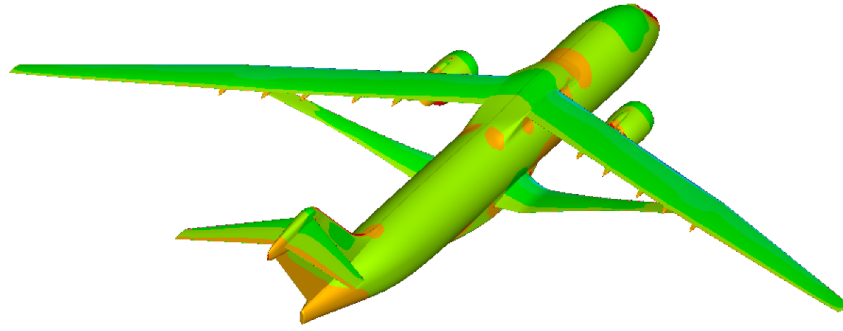


Figure 8 Pressure Coefficient Contour on the TTBW 1G Geometry Config-138 Surface at Mach 0.2, $\alpha = 2^\circ$ and $Re = 0.96 \times 10^6$.

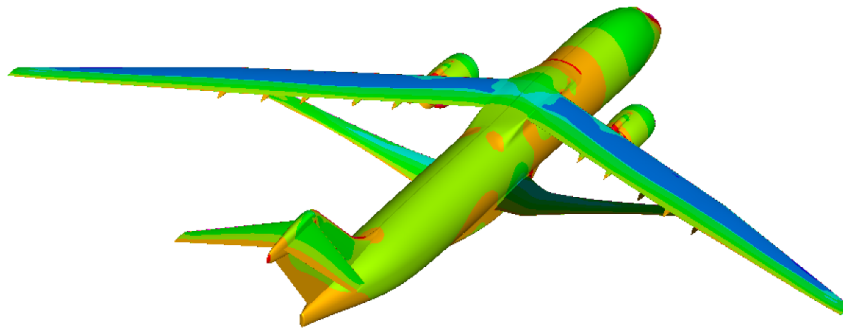


Figure 9 Pressure Coefficient Contour on the TTBW 1G Geometry Config-138 Surface at Mach 0.8, $\alpha = 2^\circ$ and $Re = 1.70 \times 10^6$.

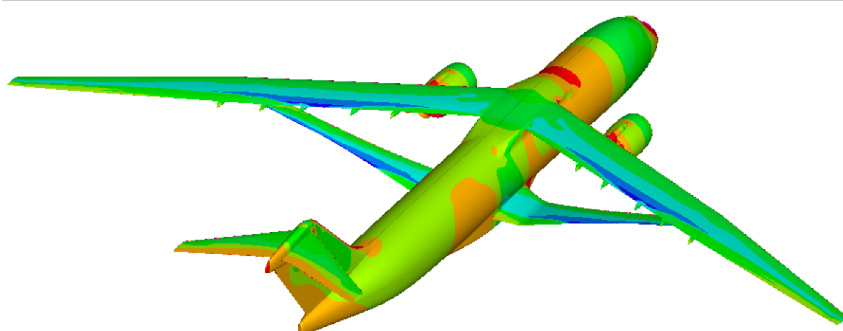
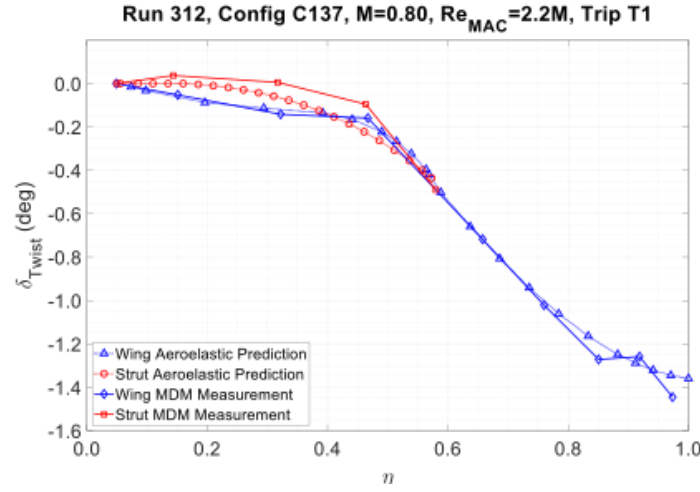


Figure 10 Pressure Coefficient Contour on the TTBW 1G Geometry Config-138 Surface at Mach 0.92, $\alpha = 2^\circ$ and $Re = 1.70 \times 10^6$.

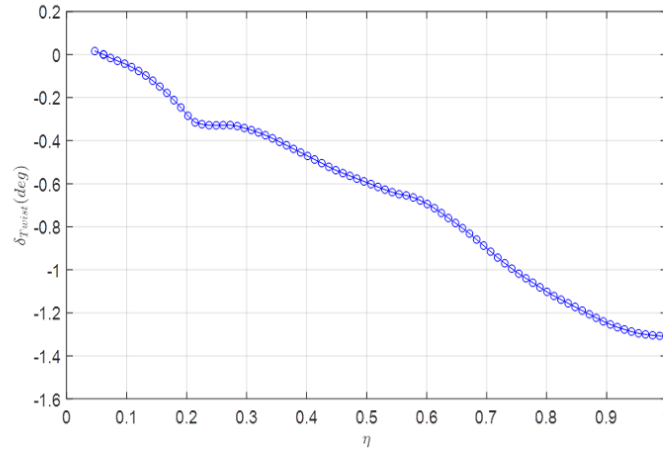
To improve the comparison between the computation results and wind tunnel data, it is necessary to apply an aeroelastic twist correction at wind tunnel Reynolds number. Ideally, this should be done using NASTRAN FEM

of wind tunnel model which is not available, but full-scale NASTRAN FEM is available. A correction procedure is developed to estimate the aeroelastic twist correction of the wind tunnel model.

Firstly, the aeroelastic washout twist at flight Reynolds number is calculated using FUN3D and compared with that at wind tunnel Reynolds number. FUN3D aeroelastic solution provides generalized displacements which are used to compute the wing deformation.¹¹ Figure 11 shows the aeroelastic washout twist at the flight and wind tunnel Reynolds number and design C_L 0.695. Although there is some discrepancy near the wing inboard region, the wing tip washout twists are similar. So it is valid to correct the aeroelastic twist at wind tunnel Reynolds number using the aeroelastic twist at flight Reynolds number.



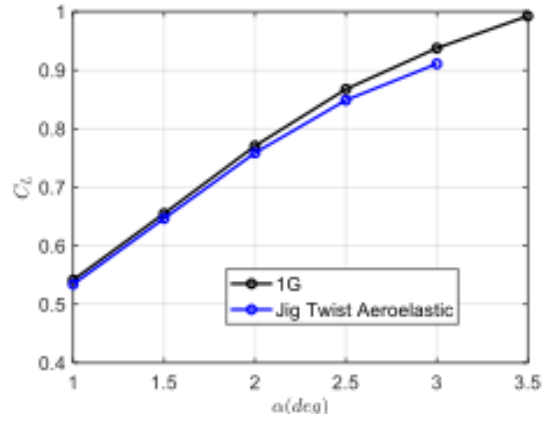
(a) Wind tunnel Reynolds (Credit: Harrison et. al.¹²)



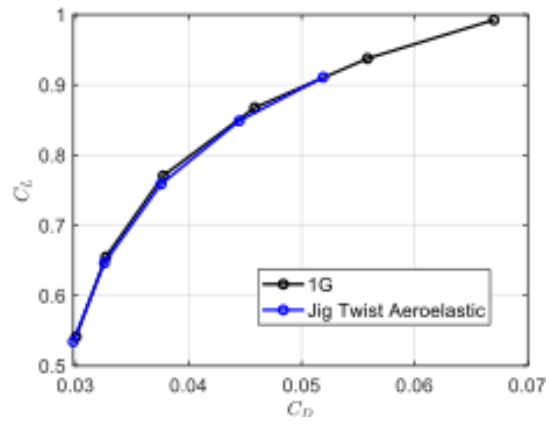
(b) Flight Reynolds

Figure 11 Aeroelastic Washout Twist of the Mach 0.8 TTBW aircraft at design C_L 0.695 .

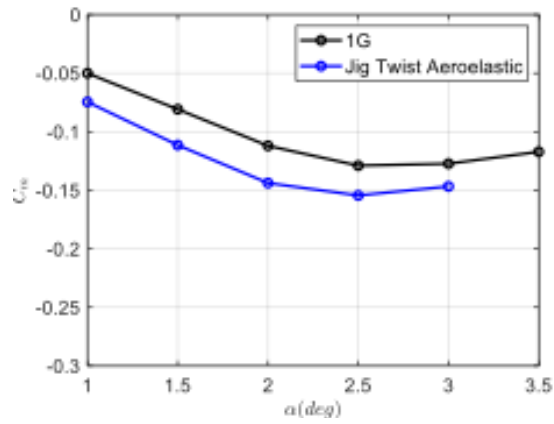
Figure 12 shows the lift, drag, and pitching moment coefficients computed for 1G OML and jig OML aeroelastic solutions at flight Reynolds number. The incremental aerodynamic coefficients are calculated using the 1G OML and jig OML aeroelastic solutions. Figure 13 shows the incremental of lift, drag, and pitching moment coefficients between 1G OML and jig OML aeroelastic solutions at flight Reynolds number.



(a) Lift Curve

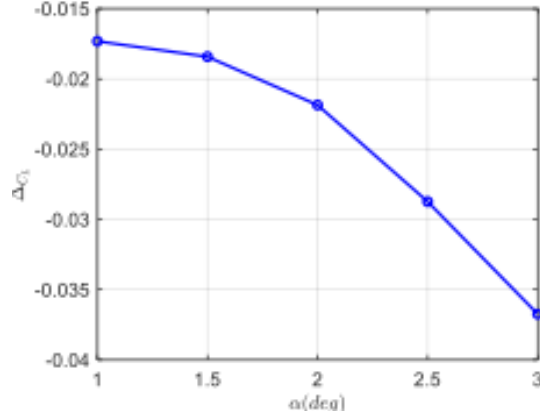


(b) Drag Polar

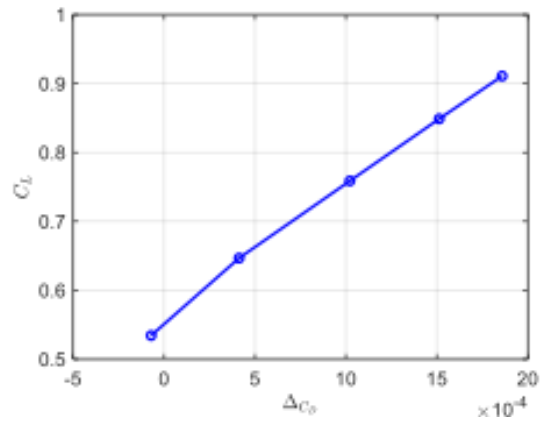


(c) Pitch Moment Curve

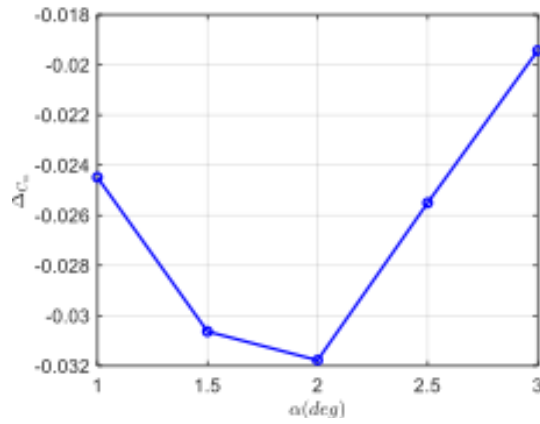
Figure 12 Comparison of Lift, Drag, and Pitching Moment Predictions for the TTBW Geometry at Mach 0.8 and $Re = 14.0 \times 10^6$.



(a) Lift Curve



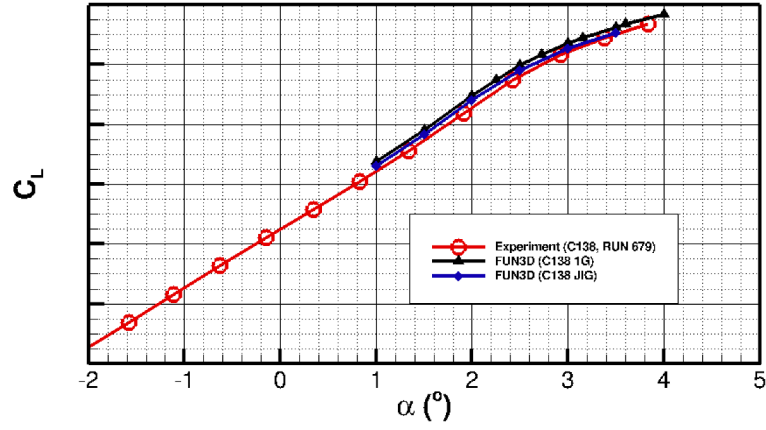
(b) Drag Polar



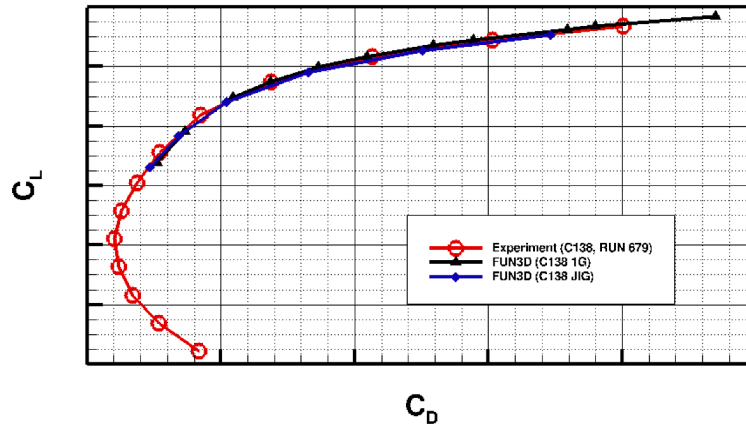
(c) Pitch Moment Curve

Figure 13 Incremental of Lift, Drag, and Pitching Moment Predictions for the TTBW Geometry.

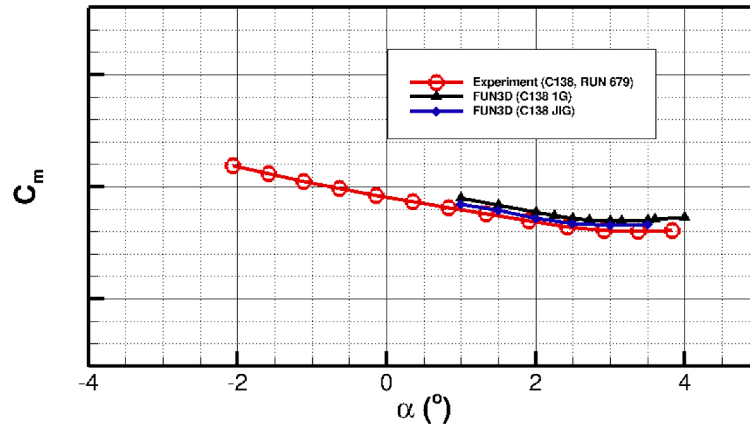
Using the developed corrections the 1G OML solution at wind tunnel Reynolds number with incremental aero coefficients at flight Reynolds is corrected to obtain estimates of the jig twist OML aero coefficients at wind tunnel Reynolds number. Figure 14 shows the lift, drag, and pitching moment coefficients computed by FUN3D as well as Run 679¹² wind tunnel data. With the developed aeroelastic model deformation correction the validation is improved. The discrepancy is reduced when the model deformation is accounted.



(a) Lift Curve



(b) Drag Polar



(c) Pitch Moment Curve

Figure 14 Comparison of Lift, Drag, and Pitching Moment Predictions for the TTBW Geometry Config-138 at Mach 0.8 and $Re = 1.7 \times 10^6$.

III. Flight Jig Twist Optimization

The jig shape OML geometry is not a flight jig shape, which accounts for the wing aeroelastic wash-out twist for the full-scale vehicle at the design flight condition, but is a jig shape designed for a wind tunnel model.. Thus, the wind tunnel jig shape model is suitable for comparisons to wind tunnel data, but not necessarily suitable for generating a model of full-scale aerodynamic performance. Also, the aerodynamic performance of the wind tunnel jig shape geometry might not be optimized for the full-scale TBW aircraft at cruise flight conditions. An optimization study is conducted to obtain a flight-optimized jig twist for the Mach 0.8 TTBW configuration.

The goal of the optimization scheme is to minimize the drag coefficient of the aero-structural model of the jig shape geometry for the TTBW aircraft at design condition. The cost function is defined as:

$$J(\alpha, c) = C_D, \quad (1)$$

while subject to constant lift and zero pitch moment constraints. Design variables include angle of attack α and the coefficients of a shape function $c = [c_1, \dots, c_N]$ which parameterize the jig twist such that:

$$\theta(y) = \theta_{ini}(y) + \sum_{i=1}^N c_i \phi_i(y), \quad (2)$$

where $\theta(y)$ represents the jig twist distribution along the spanwise direction, $\theta_{ini}(y)$ is the initial jig twist distribution along the spanwise direction, corresponding to the wind tunnel optimized twist model, and $\phi_i(y)$ is a shape function of degree i . Shape functions are utilized in order to limit the number of design variables for optimization as well as provide a smoother converged optimized jig twist distribution. Three different order of the Chebyshev polynomial are used as the shape function. Figure 15 shows the Chebyshev polynomial shape functions. Figure 16 shows the Chebyshev polynomial shape functions representation on the CFD mesh, which are used to deform the geometry in the optimization.

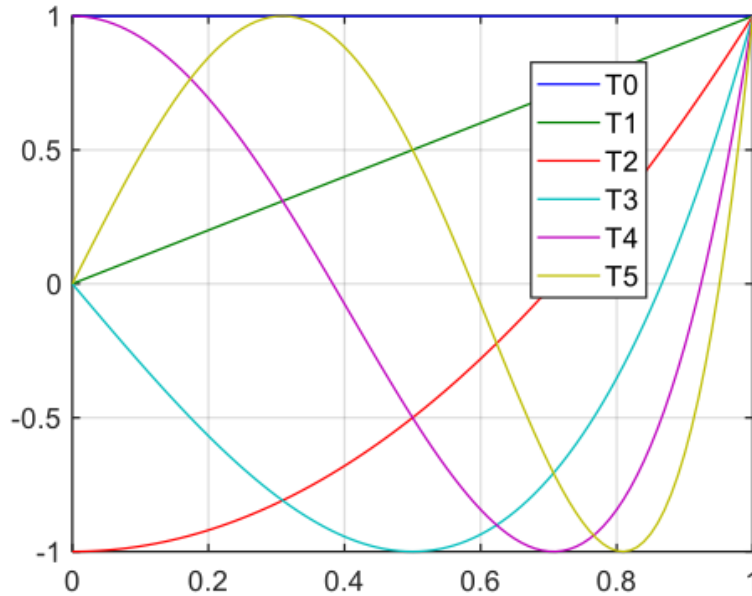


Figure 15 Chebyshev Polynomial Shape Functions

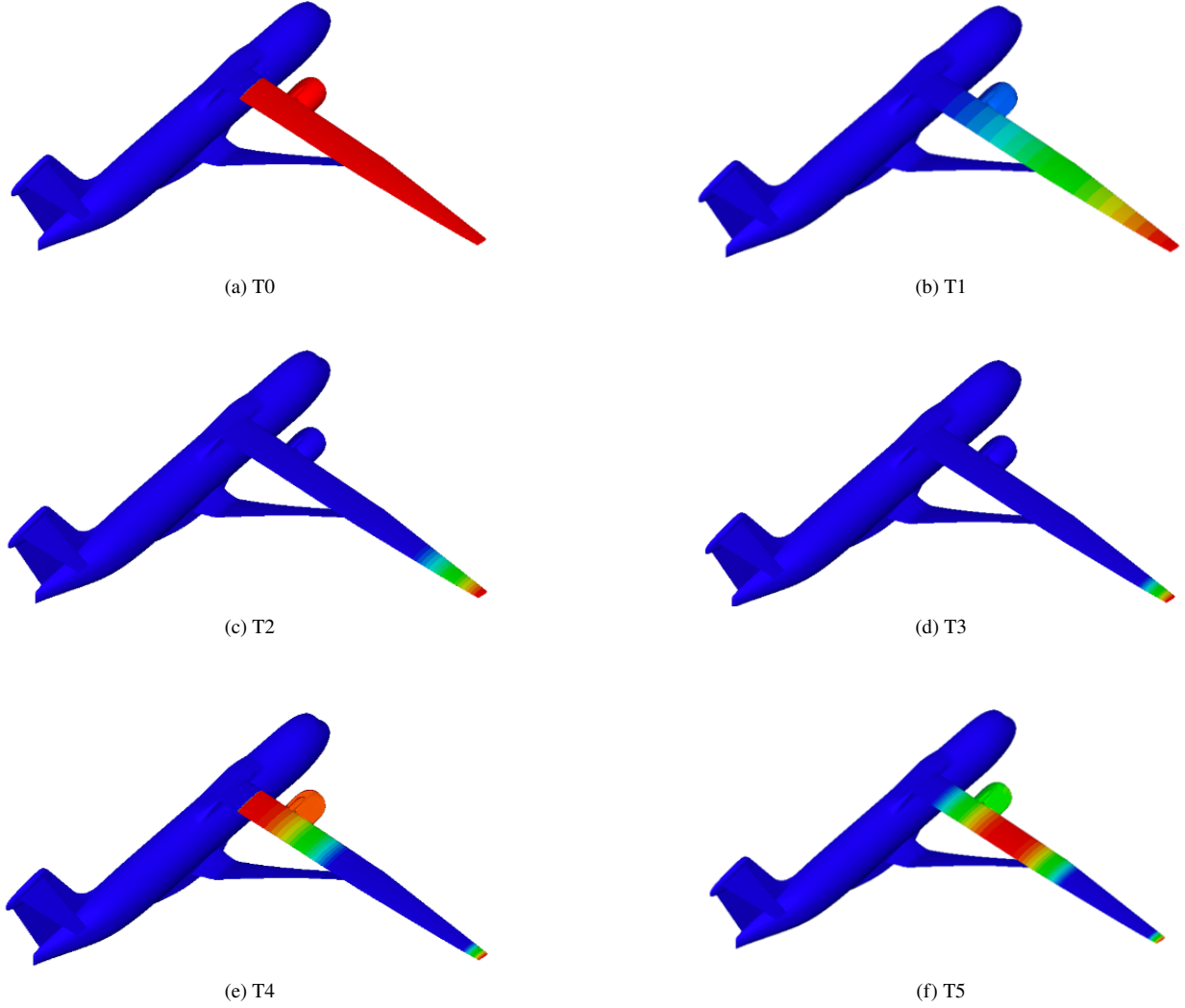


Figure 16 Chebyshev Polynomial Shape Functions on the CFD mesh.

The steepest descent algorithm for updating the design variables can be represented by the following equations:

$$\alpha_{k+1} = \alpha_k - \epsilon \cdot \frac{\partial J}{\partial \alpha} \quad (3)$$

$$c_{i_{k+1}} = c_{i_k} - \epsilon \cdot \frac{\partial J}{\partial c_i}. \quad (4)$$

Here, the design variable at iteration k is updated based on the partial derivative of the cost function with respect to the design variable, which is calculated using a small-perturbation, second-order central difference scheme, and ϵ is a step size term.

The optimization procedure begins by initializing both the TTBW geometry and the parameterization of the jig twist. A baseline aero-structural solution is established by the wind tunnel jig twist model. A gradient is established based on the effect of the small perturbations such that the design variables can be updated relative to their respective cost function partial derivatives. This small perturbation iterative procedure is repeated until the cost function converges.

The jig twist optimization produces a flight optimized jig twist distribution and changes as shown in the Figure 17 and Figure 18. The flight optimized jig twist distributions using the three different order of shape functions are very similar.

Figure 19 shows the pressure contour comparison of the wind tunnel jig, flight optimized jig using different order of the Chebyshev polynomial at design condition. The optimized jig twist result in more uniform pressure distribution on the aircraft wing surface and thereby reduce the drag coefficient. The aerodynamic parameters are presented in the Table 1. The 5th order shape function produces largest drag coefficient reduction about 5.7 ccunts.

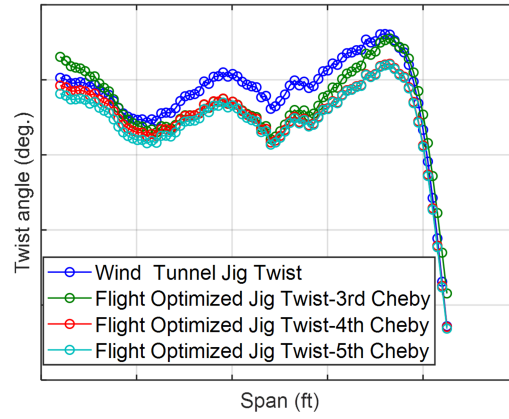


Figure 17 Flight Optimized Jig Twist Distribution.

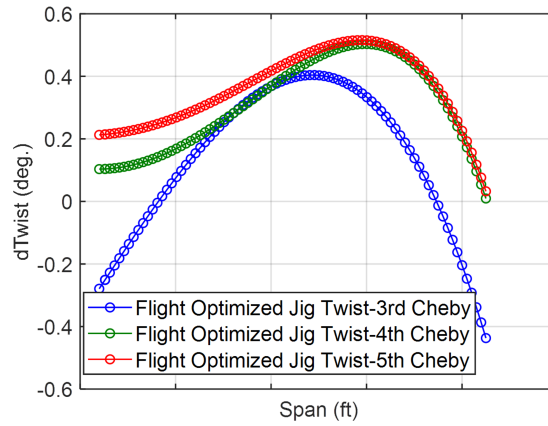


Figure 18 Flight Optimized Jig Twist change Distribution.

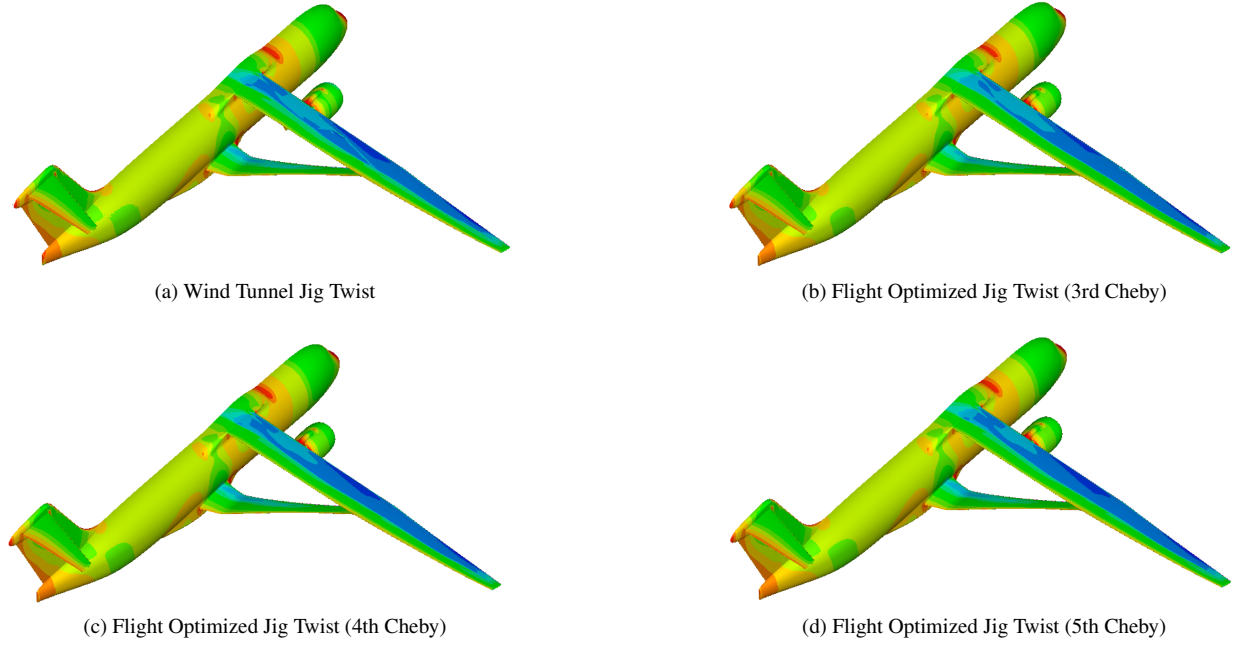


Figure 19 Pressure Coefficient Contour on the Mach 0.8 TTBW Surfaces at $M_\infty = 0.8$ and $C_L = 0.695$

Table 1 Jig Twist Optimization Results for $C_L = 0.695$

Model	$\alpha_{trim}(\text{deg.})$	C_L	C_D	ΔC_D (counts)	$\Delta C_D / C_{D_{jig}}$
Wind Tunnel Jig Twist	1.695	0.695	0.03273	-	-
Flight Optimized Jig Twist (3rd Cheby)	1.833	0.695	0.03221	5.2	1.59%
Flight Optimized Jig Twist (4th Cheby)	1.853	0.695	0.03217	5.6	1.71%
Flight Optimized Jig Twist (5th Cheby)	1.862	0.695	0.03216	5.7	1.74%

Conclusions

In this paper a jig twist optimization study of the Mach 0.8 Transonic Truss-Braced Wing (TTBW) aircraft using FUN3D is performed. Firstly, the solver is validated against wind tunnel test data. An aeroelastic model deformation correction method is developed for the wind tunnel model to improve the validation. The flight condition corresponding to Mach 0.8 and design lift coefficient 0.695 is selected for the TTBW aircraft jig twist optimization to reduce the drag coefficient. Three different orders of the Chebyshev polynomials are used as shape function. The preliminary optimization results show that the Mach 0.8 TTBW aircraft with the optimized jig twist achieves a drag reduction of about 5.7 counts when 5th order Chebyshev polynomials are used as shape function.

Acknowledgment

The authors wish to acknowledge NASA Advanced Air Transport Technology project for the funding support of this work. The authors also acknowledge Boeing Research and Technology and in particular Christopher Droney, Neal Harrison, Michael Beyar, Eric Dickey, and Anthony Sclafani, along with the NASA technical POC, Gregory Gatlin, for their research conducted under the NASA BAART contracts NNL10AA05B and NNL16AA04B. The research published in this paper is made possible by the technical data and wind tunnel test data furnished under these BAART contracts.

References

- ¹ Bhatia, M., et. al., “Structural and Aeroelastic Characteristics of Truss-Braced Wing: A Parametric Study,” *Journal of Aircraft*, Vol 49, No. 1, 2012.
- ² Gundlach, J. F., Tetrault, P. A., Gern, F. H., Nagshineh-Pour, A. H., Ko, A., Schetz, J. A., et. al., “Conceptual Design Studies of a Strut-Braced Wing Transonic Transport,” *Journal of Aircraft*, Vol. 37, No. 6, 2000.
- ³ Gur, O., Bhatia, M., Schetz, J.A., Mason, W. H., Kapania, R. K., and Mavris, D. N., “Design Optimization of a Truss-Braced Wing Transonic Transport Aircraft,” *Journal of Aircraft*, Vol. 47, No. 6, 2010.
- ⁴ Harrison, N. A., Beyar, M. D., Dickey, E. D., Hoffman, K., Gatlin, G.M. and Viken, S. A., “Development of an Efficient Mach=0.80 Transonic Truss-Braced Wing Aircraft,” *AIAA SciTech Conference*, AIAA-2020-0011, January 2020.
- ⁵ Biedron, R. T., et al., “FUN3D Manual 13.2,” NASA TM-2017-219661, Aug. 2017
- ⁶ Lee-Rausch, E. M., Hammond, D. P., Nielsen, E. J., Pirzadeh, S. Z., and Rumsey, C. L., “Application of the FUN3D Unstructured-Grid Navier-Stokes Solver to the 4th AIAA Drag Prediction Workshop cases,” *AIAA Aviation Conference*, AIAA-2010-4511, January 2019.
- ⁷ Roe, P. L., “Approximate Riemann Solvers, Parameter Vectors and Difference Schemes,” *Journal of Computational Physics*, Vol. 46, No. 2, 1980, pp. 357-378
- ⁸ Venkatakrishnan, V., “Convergence to Steady State Solutions of the Euler Equations on Unstructured Grids with Limiters,” *Journal of Computational Physics*, Vol. 118, No. 1, 1995, pp. 120-130
- ⁹ Spalart, P. R. and Allmaras, S. R., “A One-Equation Turbulence Model for Aerodynamic Flows,” *AIAA Science and Technology Forum and Exposition*, AIAA-1992-0439, January 1992.
- ¹⁰ Biedron, R. T. and Thomas, J. L., “Recent Enhancements To The FUN3D Flow Solver For Moving-Mesh Applications,” *AIAA* 2009-1360, Jan. 2009
- ¹¹ Xiong, J., Nguyen, N., and Bartels, R. E., “Aeroelastic Analysis of Mach 0.8 Transonic Truss-Braced Wing Aircraft,” *AIAA Science and Technology Forum and Exposition*, AIAA-2022, Jan. 2022.
- ¹² Harrison, N. A., Sclafani, A. J., Beyar, M. D., Dickey, E. D., and Intravartolo, N. M., “Subsonic Ultra Green Aircraft Research: Phase IV Final Report: Vol.2 Transonic Truss-Braced Wing High-Speed Test Report,” *NASA/CR-2020-000000*, 2020.