

Aeroelastic Simulation of Wind Tunnel Scale Aspect Ratio 13.5 Common Research Model with Trailing Edge Mini-Flaps

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 computation study of an aspect ratio 13.5 wind tunnel scale Common Research Model (CRM) with trailing edge mini-flaps using FUN3D. The aeroelastic simulations are conducted under free-air and inside wind tunnel conditions. The NASA Langley Research Center Transonic Dynamic Tunnel (TDT) is a closed circuit and slotted-test-section with a 16 ft $\times$ 16 ft test section. The structure mode shapes are extracted from the latest updated NASTRAN Finite-Element Model (FEM) model. A dynamic pressure sweep is performed to determine the control reversal boundary of the trailing edge mini-flaps. The wind tunnel wall interference effects on the mini-flap control derivatives are analyzed based on the simulations.

I. Introduction

Modern aircraft design employs light-weight structures for energy efficiency. As structural flexibility increases, aeroelastic interactions with aerodynamic forces and moments can alter aircraft aerodynamics significantly.¹ One option for managing the aeroelastic behavior of the aircraft is through control system design. The control system could be made to both suppress undesirable motion and shape the flexible structure in pursuit of improved performance goals. The concept of variable-camber continuous trailing-edge flap (VCCTEF) for the active control of an aeroelastic wing developed by NASA was proposed by Nguyen in 2010.^{2,3} The use of VCCTEF for the active control of an aeroelastic wing such as suppressing flutter, stabilizing the vehicle response to gusts, and reducing drag have been extensively studied.^{1,4,5,6} Nguyen et al.¹ first demonstrated real-time drag optimization of the Common Research Model (CRM) in a low-speed wind tunnel experiment using the VCCTEF. In order to further discover the capability of the trailing-edge flap for the real-time drag optimization, maneuver load alleviation, and gust load alleviation, Boeing develops Integrated Adaptive Wing Technology Maturation (IAWTM) for an aspect ratio 13.5 CRM with distributed trailing edge flaps under a NASA contract with the NASA Advanced Air Transport Technology (AATT) project. The aspect ratio 13.5 CRM is developed from the original aspect ratio 8.3 CRM.⁷ The aspect ratio 13.5 CRM configuration employs a distributed mini-plain flap system which comprises 10 small trailing edge flaps positioned along the wing span. These mini-plain flaps can be used for a real-time drag optimization, maneuver load alleviation, and gust load alleviation strategies. Figure 1 illustrates the aspect ratio 13.5 wind-tunnel scale CRM configuration. The experimental plan to conduct active-control wind tunnel experiments in NASA Transonic Dynamic Tunnel (TDT) at NASA Langley Research Center. To support the wind tunnel experiment and the development of the real-time drag optimization and maneuver load alleviation algorithms using the mini-plain flaps, a computationally efficient aero-structural analysis solver is desired to generate a reliable aerodynamic database.

A previous study was conducted to develop an aeroelastic model of the wind tunnel scale CRM model.⁸ However the wind tunnel wall interference effects were not included in the simulation. The transonic wind tunnel is a 16 ft $\times$ 16 ft slotted-wall test section wind tunnel. Figure 2 illustrates the wind tunnel test section and layout with operational schedule for the re-entry flaps. The CRM model wing tip extends too close to the test section wall and could raise a concern about the accuracy of CFD prediction of the control derivatives of the flaps. In this paper, a computational approach is used to investigate the control derivatives of the flaps and the wall interference effects using FUN3D CFD solver. The simulations are conducted under free-air and open slots with notional cylindrical plenum conditions.

*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

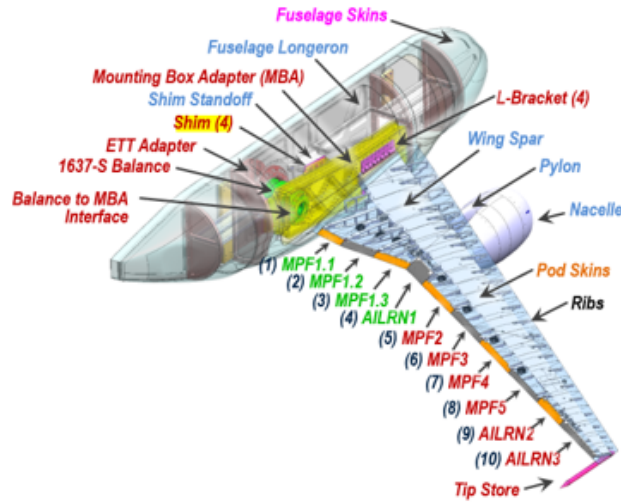
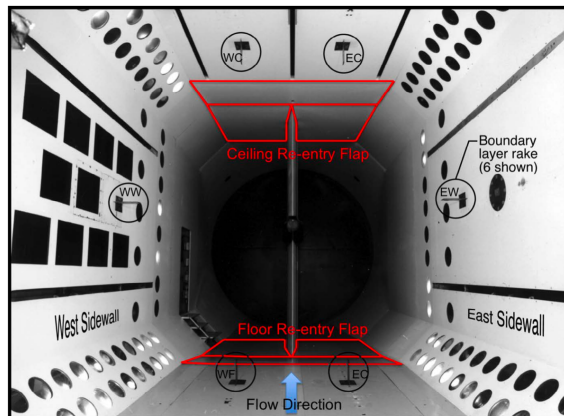
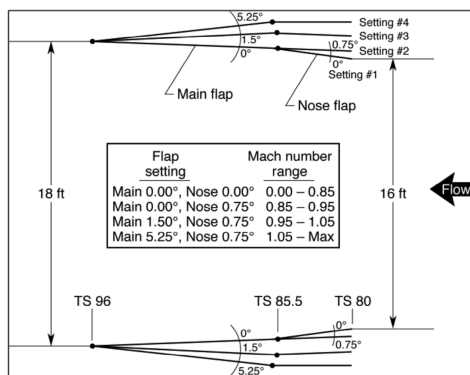


Figure 1 Wind Tunnel Scale Common Research Model (CRM)



(a) Wind Tunnel Test Section



(b) Re-entry flaps schedule as a function of Mach number

Figure 2 TDT Wind Tunnel Test Section and the Layout with Operational Schedule for the Re-entry Flaps. (Credit: Chwalowski et al.⁹)

II. Computational Approach

A. Numerical Code

The computational fluid dynamics code used in this study is FUN3D,^{10,11} 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 that delimits the neighboring control volumes, the inviscid fluxes are computed using an approximate Riemann solver based on the values on either side of the interfaces. The Roe flux difference splitting¹² is used in the current study. For second-order accuracy, the interface values are obtained by extrapolation of the control volume centroidal values, based on the gradients computed at the mesh vertices, using an unweighted least squares technique. The Venkatakrishnan¹³ limiter is used in the current study to limit the reconstructed values when necessary. In this study, the tetrahedral mesh with prism layers is 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 backward 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-Allmaras¹⁴ (S-A) is used in this study.

Figure 3 shows the surface mesh of the geometry without the wind tunnel walls. A standoff spacer about 1.25" is included in the model to account the wind tunnel wall boundary layer effects. The total number of the nodes for the mesh is about 60 million. The volume mesh is comprised of tetrahedral elements and a prism layer near the wall. The prism layer is used to resolve the turbulent boundary layer. The y^+ of the first cell from the wall is less than 1.

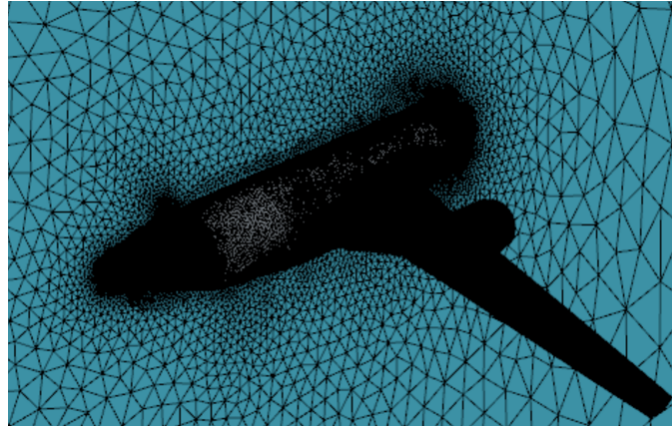


Figure 3 CRM CFD Mesh

B. Aeroelastic Simulation

The static aeroelastic simulation module in FUN3D is used for the aeroelastic simulation. The mode shapes are extracted from full NASTRAN model. Figure 4 shows the updated NASTRAN model AWT04 provided by Boeing. Figure 5 shows the updated wind tunnel scale CRM first six mode shapes. The contour color represents the nodal displacement. Figure 6 shows the pressure coefficient contour on the CRM surfaces at Mach 0.85, $q_\infty = 230$ psf, and $\alpha = 0^\circ$.

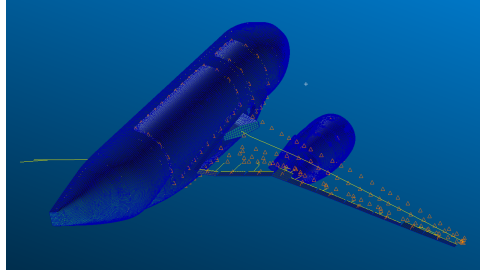
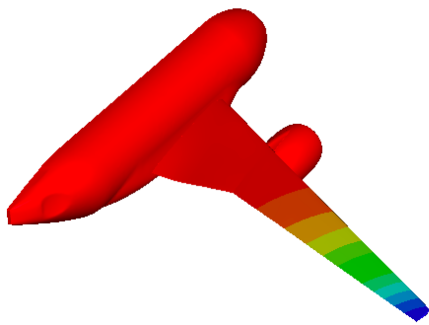
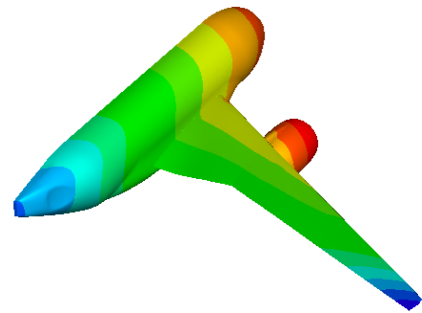


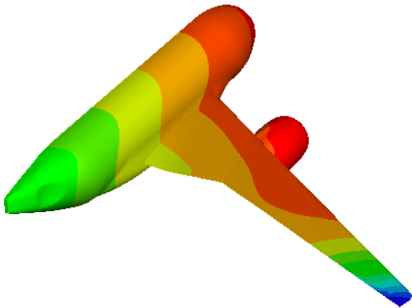
Figure 4 Wind Tunnel Scale CRM NASTRAN FEM Model AWT04



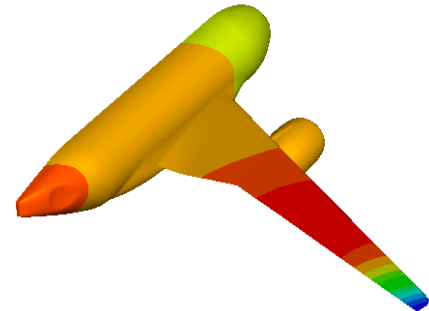
(a) 1st Mod



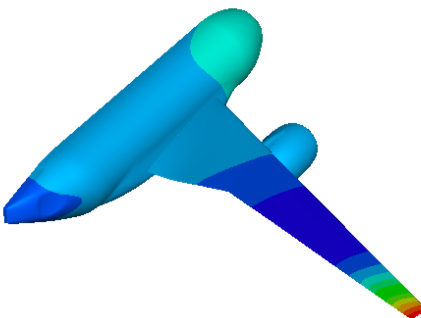
(b) 2nd Mode



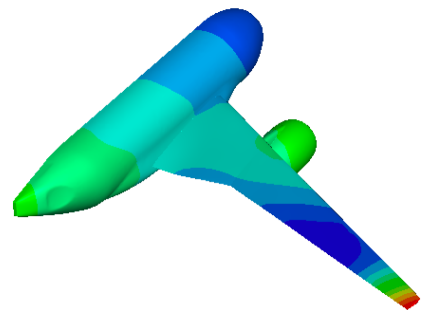
(c) 3rd Mode



(d) 4th Mode



(e) 5th Mode



(f) 6th Mode

Figure 5 CRM Mode Shapes

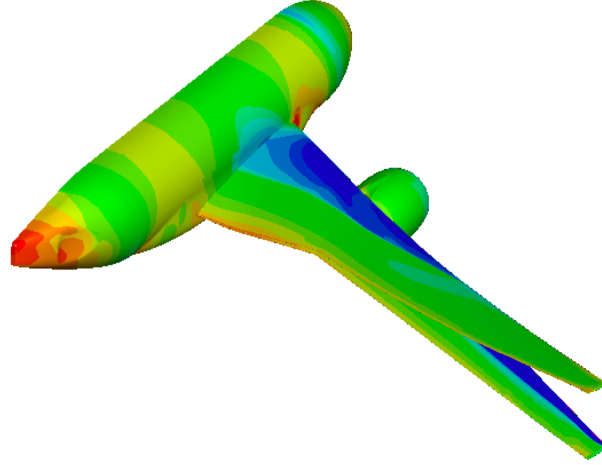


Figure 6 Pressure Coefficient Contour on the CRM Surfaces at Mach 0.85, $q_{\infty} = 230$ psf and $\alpha = 0^{\circ}$

III. Aeroelastic Modeling of Trailing Edge Mini-Flaps

A. Mini-Flap Model

There are 10 mini-plain trailing edge flaps on the CRM. Table 1 lists the index of the flaps which are used in this paper. Figure 7 shows the planform of the flaps. The red line in the figure represents the flaps. Figure 8 illustrates the flap deflection definition. The deflection angle is positive when the flap is deflected downward. Deflected mini-flaps are created using the process developed in Ref.⁶ The various mini-flaps undergo rigid body rotations about the hinge line. In this study the gap between the mini-flaps are not modeled. A radial basis function smoother applied between mini-flaps segments ensures surface continuity between the mini-flaps. The surface with the commanded mini-flap rotations is input into the FUN3D code and the volume mesh is deformed. Figure 9 shows the model for the 10 mini-flaps.

Table 1 CRM Flap Index

MPF1.1	Flap 1
MPF1.2	Flap 2
MPF1.3	Flap 3
AILRN1	Flap 4
MPF2	Flap 5
MPF3	Flap 6
MPF4	Flap 7
MPF5	Flap 8
AILRN2	Flap 9
AILRN3	Flap 10

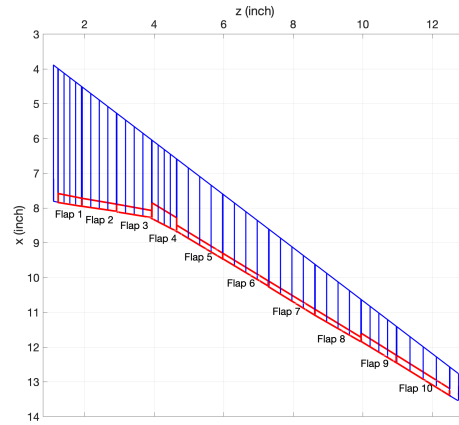


Figure 7 CRM Mini-Flap Planform

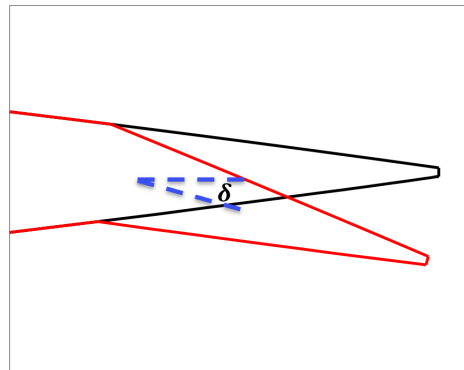


Figure 8 CRM Mini-Flap Deflection Definition

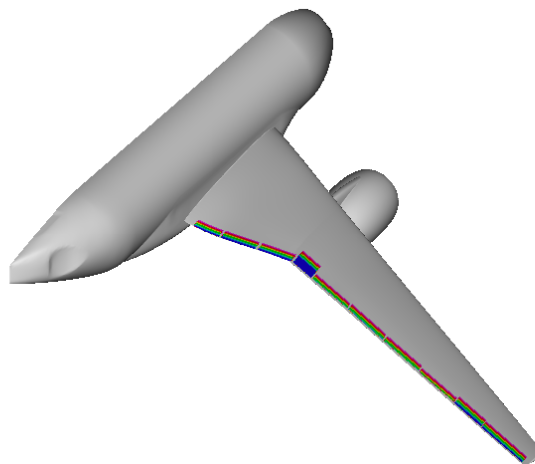


Figure 9 Modes for CRM mini-flaps.

B. Steady-state Simulations

Firstly, the static aeroelastic simulations are conducted for the CRM with flaps deflected from -10° to 10° at Mach 0.85, dynamic pressure 230 psf, and angles of attack -2° , 0° and 2° . Figure 10-12 shows the pressure contours for the 10 flaps deflected 10° at angle of attack 0° . Figure 13 - 15 show the lift and drag coefficients for the 10 flaps. For the mini-flaps 1-7, the lift and drag coefficients increase as the flap deflection angle increases. However, for the mini-flaps 8-10, the lift and drag coefficients decrease when the flap deflection angle increases due to aeroelastic effects, which indicates the control reversal behavior.

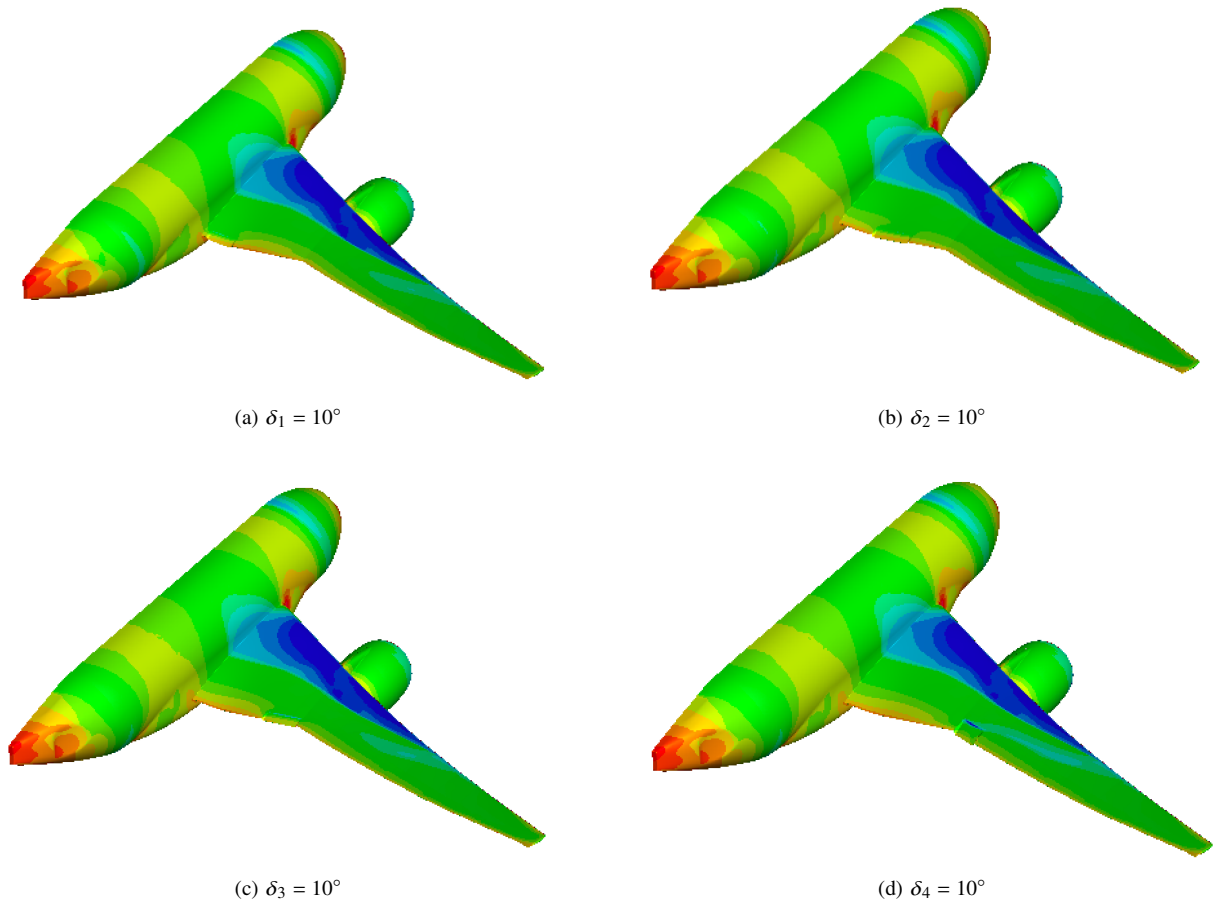
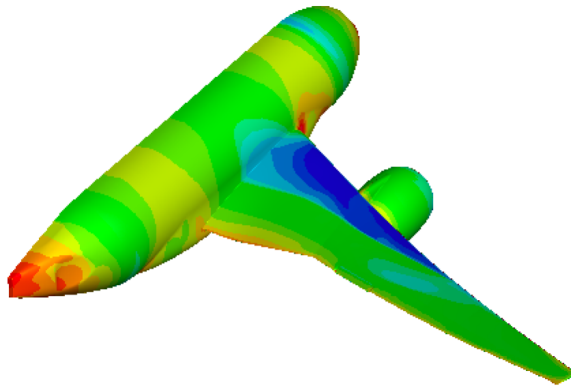
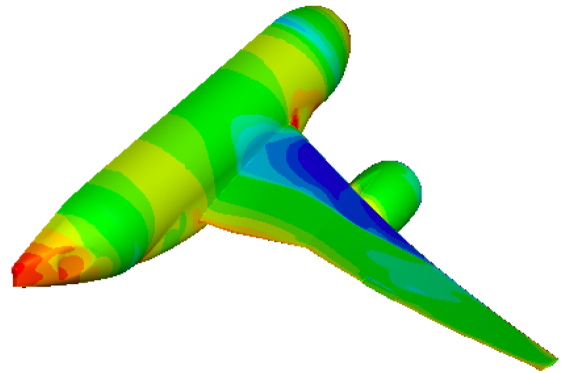


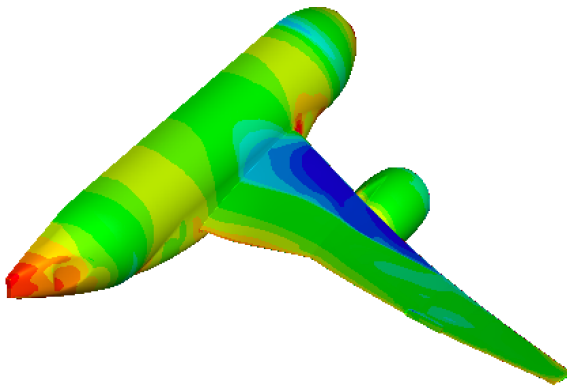
Figure 10 Pressure contour for the flaps 1-4 at Mach 0.85, $q_\infty = 230$ psf and $\alpha = 0^\circ$



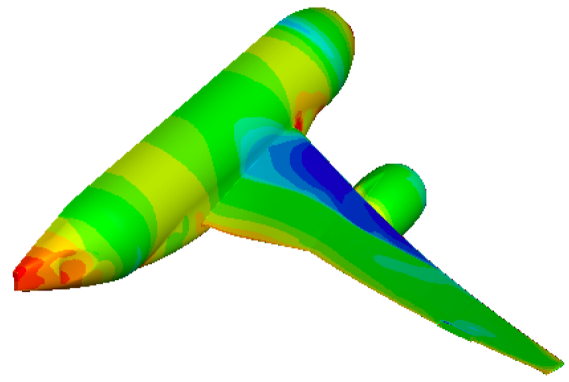
(a) $\delta_5 = 10^\circ$



(b) $\delta_6 = 10^\circ$

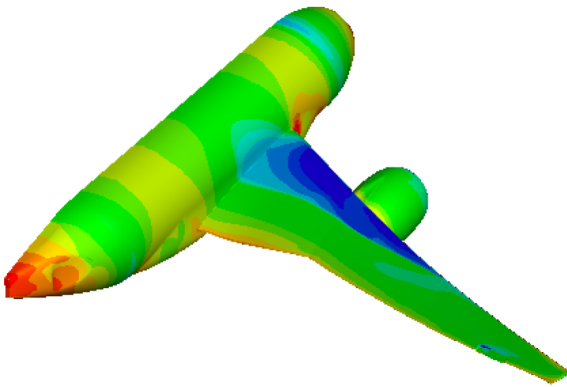


(c) $\delta_7 = 10^\circ$

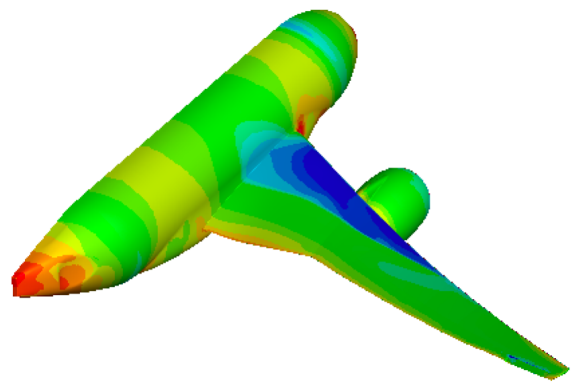


(d) $\delta_8 = 10^\circ$

Figure 11 Pressure contour for the flaps 5-8 at Mach 0.85, $q_\infty = 230$ psf and $\alpha = 0^\circ$



(a) $\delta_9 = 10^\circ$



(b) $\delta_{10} = 10^\circ$

Figure 12 Pressure contour for the flaps 9-10 at Mach 0.85, $q_\infty = 230$ psf and $\alpha = 0^\circ$

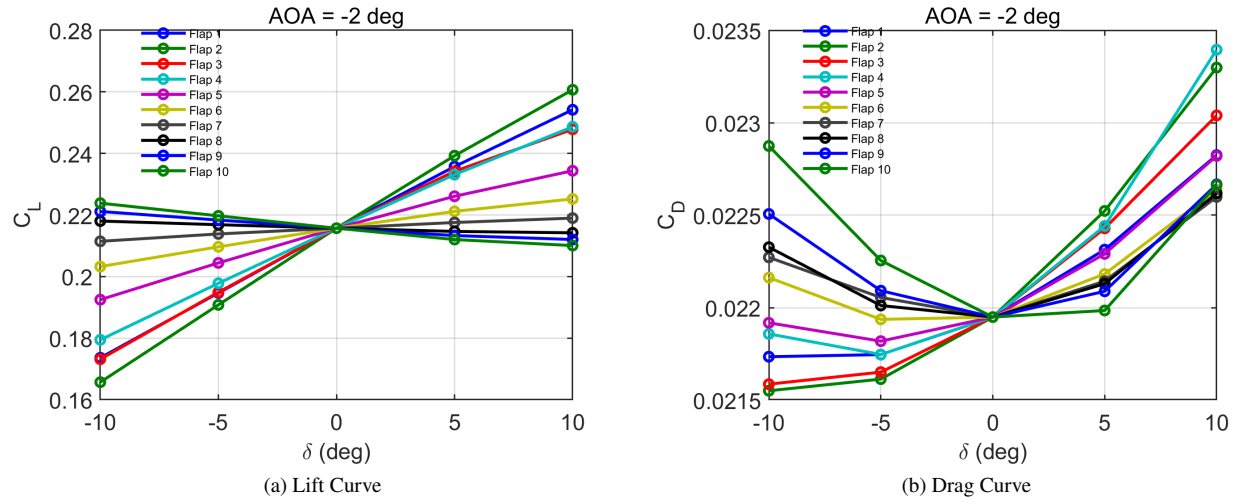


Figure 13 Lift and Drag Coefficients for the 10 flaps at Mach 0.85, $q_\infty = 230$ psf and $\alpha = -2^\circ$

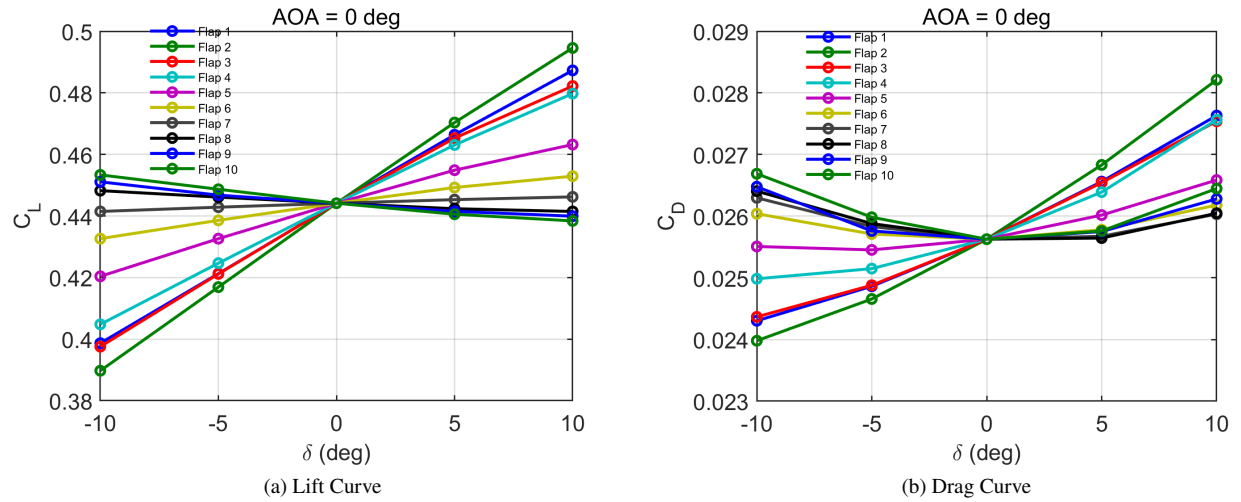


Figure 14 Lift and Drag Coefficients for the 10 flaps at Mach 0.85, $q_\infty = 230$ psf and $\alpha = 0^\circ$

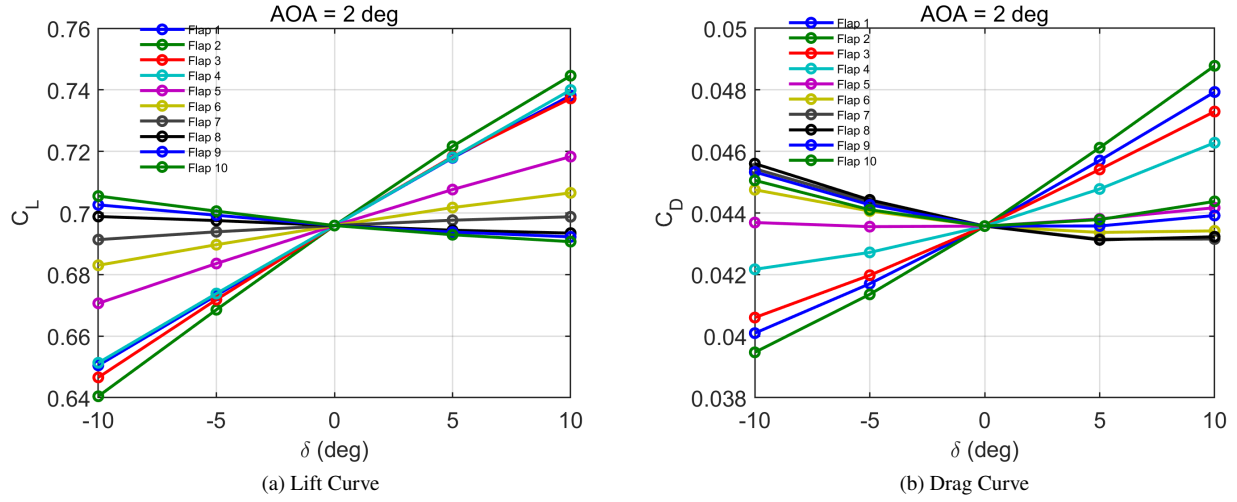
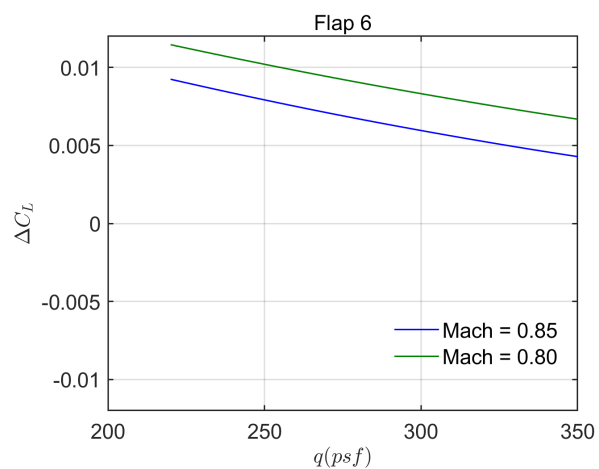


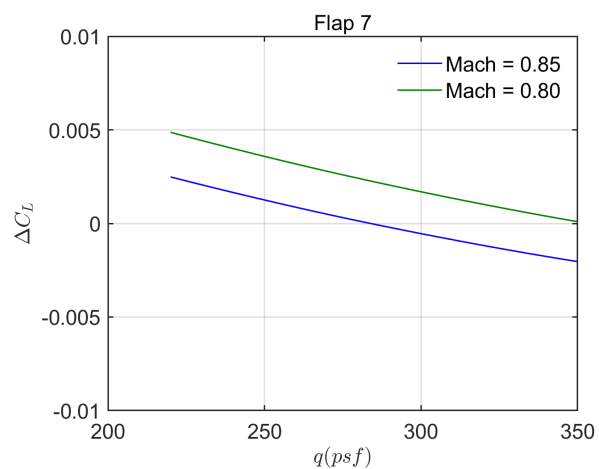
Figure 15 Lift and Drag Coefficients for the 10 flaps at Mach 0.85, $q_\infty = 230$ psf and $\alpha = 2^\circ$

C. Control Reversal Boundary

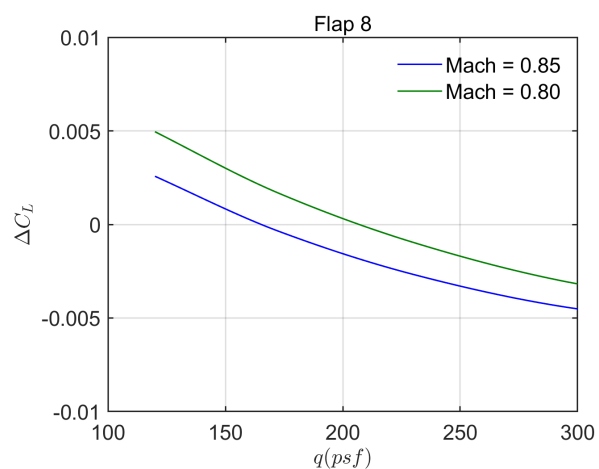
The dynamic pressure sweep simulations are performed to determine the control reversal boundaries for the flaps at Mach 0.80 and Mach 0.85. The incremental lift coefficient and rolling moment from FUN3D CFD simulations are extracted to determine the control reversal boundary. Figure 16 shows the incremental lift coefficients for the flaps 6-10 at Mach 0.80 and Mach 0.85. Figure 17 shows the incremental rolling moments for the flaps 6-10 at Mach 0.80 and Mach 0.85. Based on the incremental lift coefficient, the control reversal boundaries for Mach 0.85 are 76 psf for Flap 10, 110 psf for Flap 9, and 166 psf for Flap 8 and 290 psf for Flap 7. No control reversal is observed for flaps 6 for the maximum dynamic pressure of 350 psf. The control reversal boundaries for Mach 0.80 are 94 psf for Flap 10, 140 psf for Flap 9 and 206 psf for Flap 8. No control reversal is observed for flaps 6-8 for the maximum dynamic pressure of 350 psf. Based on the incremental rolling moment, the control reversal boundaries for Mach 0.85 are 170 psf for Flap 10, 252 psf for Flap 9, and 348 psf for Flap 8. No control reversal is observed for flaps 6 and 7 for the maximum dynamic pressure of 350 psf. The control reversal boundaries for Mach 0.80 are 191 psf for Flap 10 and 290 psf for Flap 9. No control reversal is observed for flaps 6-8 for the maximum dynamic pressure of 350 psf. The comparison of the control reversal onsets determined by incremental lift and roll moment are listed in the Table 2.



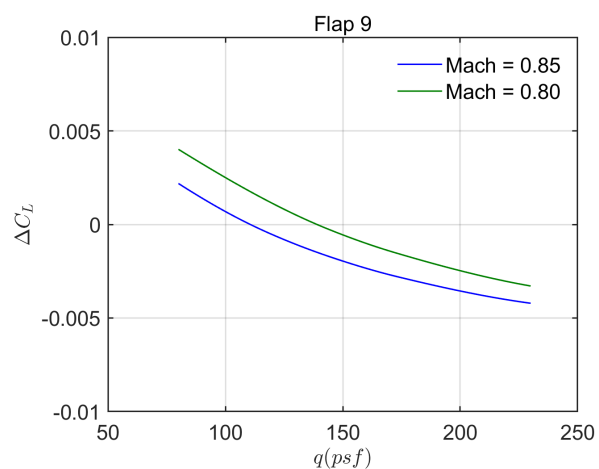
(a) Flap 6



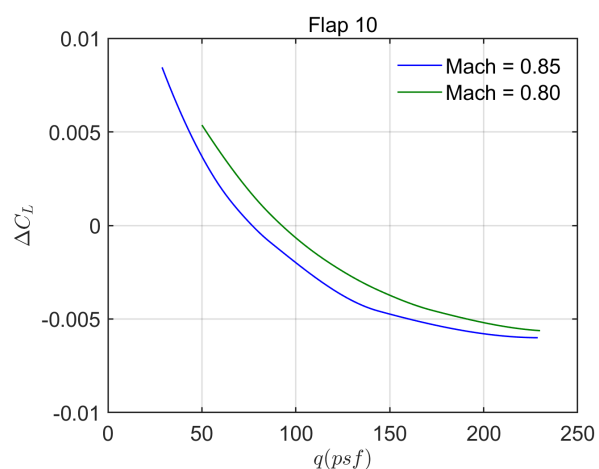
(b) Flap 7



(c) Flap 8

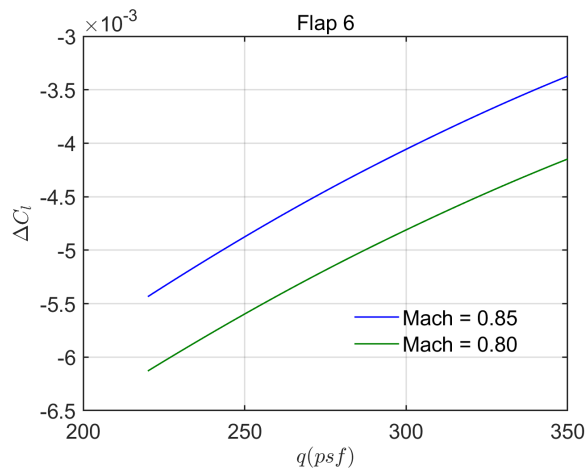


(d) Flap 9

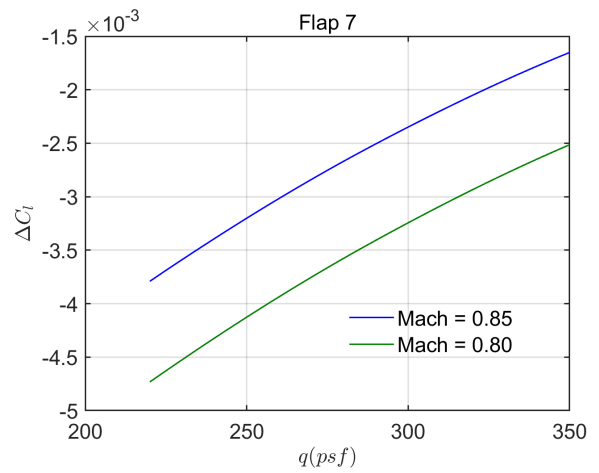


(e) Flap 10

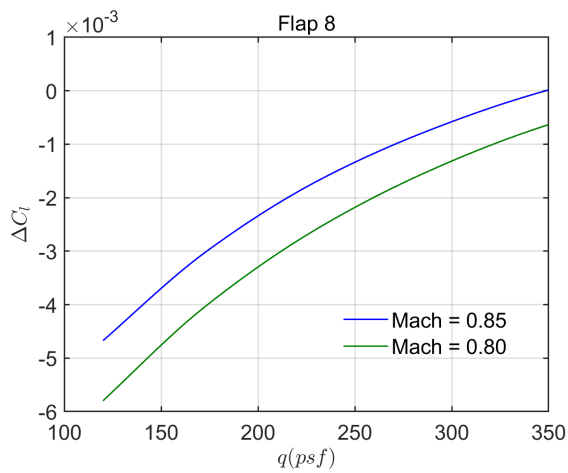
Figure 16 Incremental Lift Coefficients at Mach 0.80 and Mach 0.85



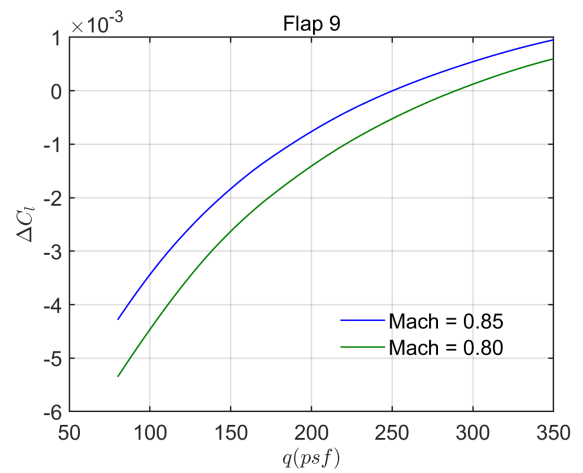
(a) Flap 6



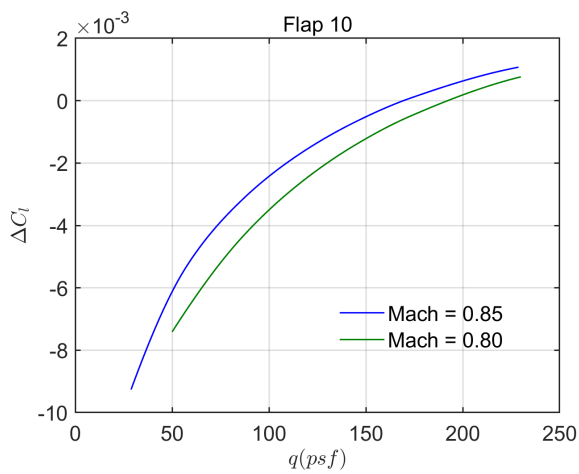
(b) Flap 7



(c) Flap 8



(d) Flap 9



(e) Flap 10

Figure 17 Incremental Rolling Moment Coefficients at Mach 0.80 and Mach 0.85

Table 2 Control Reversal Boundary

Mach	Flap 10		Flap 9		Flap 8		Flap 7		Flap 6	
	Lift force	Rolling moment	Lift force	Rolling moment	Lift force	Rolling moment	Lift force	Rolling moment	Lift force	Rolling moment
0.85	76 psf	170 psf	110 psf	252 psf	166 psf	348 psf	290 psf	-	-	-
0.80	94 psf	191 psf	140 psf	290 psf	206 psf	-	-	-	-	-

IV. Wind Tunnel Wall Interference Investigation

In this section, the simulations are conducted to examine the wall interference effects on the control derivatives of the mini-flaps. The slots in the east wall where the model is mounted on are closed. The CFD mesh also includes a notional plenum since the detail geometry of the plenum is not available. Additionally, the re-entry flaps is also modeled where the flow from the plenum reenters the wind tunnel downstream of the test section. Since the highest simulation Mach number is 0.85, the re-entry flap setting #1 is used in the simulations. Figure 18 shows the wind tunnel slotted wall with notion plenum geometry. Figure 19 shows the wind tunnel slotted wall mesh.

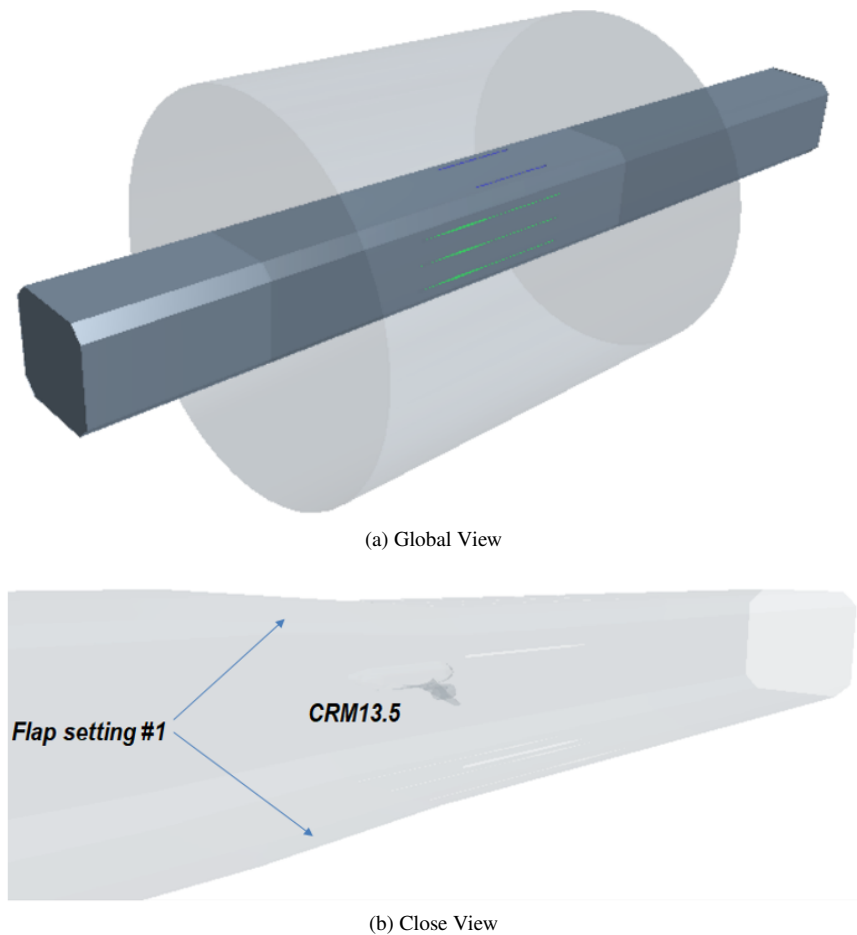


Figure 18 Wind Tunnel Slotted Wall Geometry.

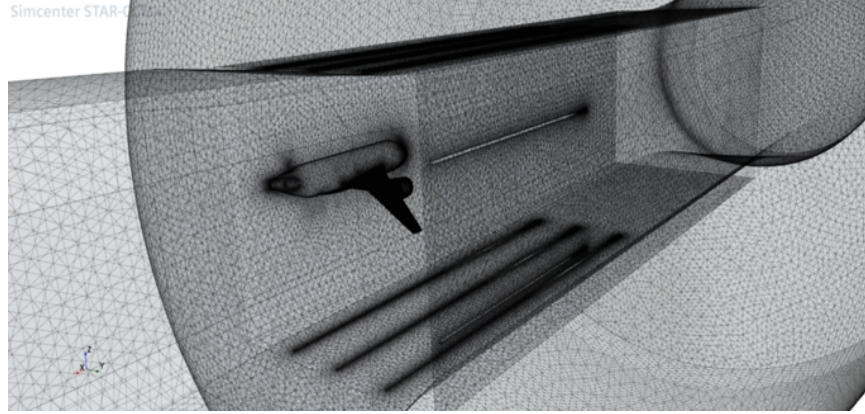
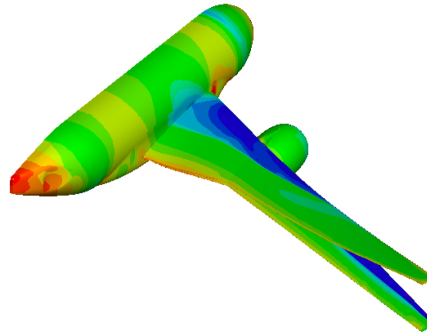
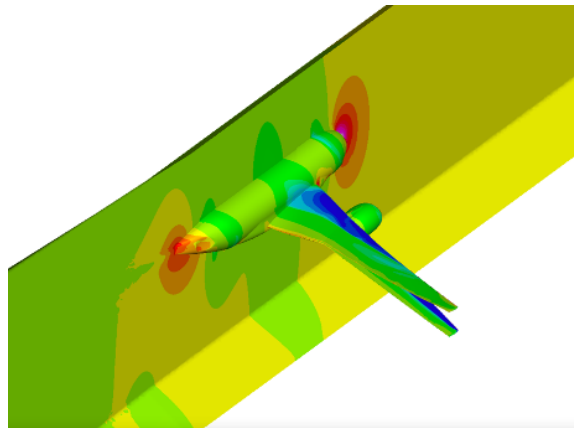


Figure 19 CRM CFD Mesh inside the Slotted WindTunnel

Figure 20 shows the flexible wing pressure contours at Mach 0.85, $q_{\infty} = 230$ psf and 0.0° angle of attack under free-air and inside the wind tunnel. Figure 21 shows the flexible wing with flap 10 deflected 10° pressure contours at Mach 0.85, $q_{\infty} = 230$ psf and 0.0° angle of attack under free-air and inside the wind tunnel. With the side wall, the shock wave turns a little bit weaker on the wing surface. The comparison of the incremental lift coefficient is presented in the Fig. 22. The flap 10 control derivative decrease due to the wind tunnel wall interference.

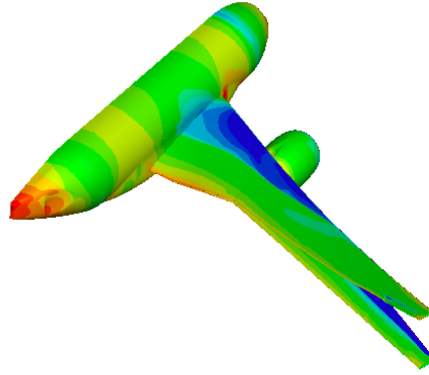


(a) In Free-air

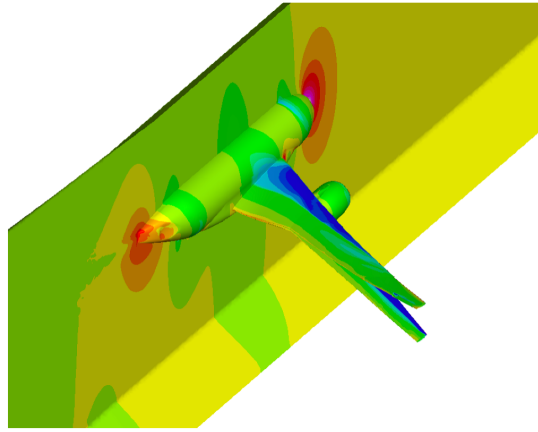


(b) In the Wind Tunnel

Figure 20 Pressure Coefficient Contour on the CRM Flexible Geometry Surfaces at Mach 0.85, $q_{\infty} = 230$ psf, and $\alpha = 0.0^{\circ}$



(a) In Free-air $\delta_{10} = 10^\circ$



(b) In the Wind Tunnel $\delta_{10} = 10^\circ$

Figure 21 Pressure Coefficient Contour on the CRM Flexible Geometry Surfaces at Mach 0.85, $q_\infty = 230$ psf, and $\alpha = 0.0^\circ$

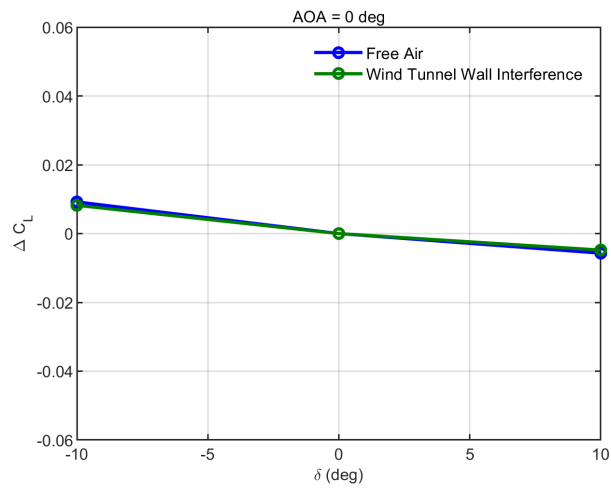


Figure 22 Comparison of Lift Coefficient of flap 10 at Mach 0.85, $q_\infty = 230$ psf and $\alpha = 0.0^\circ$.

Conclusions

In this paper, a computation study of an aspect ratio 13.5 wind-tunnel scale Common Research Model (CRM) with trailing edge mini-flaps inside a transonic wind tunnel is performed using FUN3D CFD solver. The structure mode shapes are extracted from the latest updated NASTRAN Finite-Element Model (FEM) model. An aerodynamic database is generated using FUN3D aeroelastic CRM model. A dynamic pressure sweep is performed to determine the control reversal boundary of the trailing edge mini-flaps. The incremental lift coefficient and rolling moment from FUN3D CFD simulations are extracted to determine the control reversal boundary. The wind tunnel wall interference effects on the mini-flap control derivatives are analyzed based on the simulations. The flap 10 control derivative decrease due to the wind tunnel wall interference.

Acknowledgment

The authors wish to acknowledge NASA Advanced Air Transport Technology (AATT) project for the funding support of this work. The authors also wish to acknowledge Boeing Research and Technology, in particular Dr. John Quindlen, for providing the aerodynamic data to support this work under NASA contract NNL15AA00A with the AATT project.

References

- ¹ Nguyen, N., Livne, E., Precup, N., Urnes, J., Nelson, C., Ting, E. and Lebofsky, S., "Experimental Investigation of a Flexible Wing with a Variable Camber Continuous Trailing Edge Flap Design," AIAA 2014-2441, June. 2014
- ² Nguyen, N., "Elastically Shaped Future Air Vehicle Concept," NASA Innovation Fund Award 2010 Report, October 2010, Submitted to NASA Innovative Partnerships Program,
- ³ Nguyen, N. and Urnes, J., "Aeroelastic Modeling of Elastically Shaped Aircraft Concept via Wing Shaping Control for Drag Reduction," AIAA Atmospheric Flight Mechanics Conference, AIAA-2012-4642, August 2012.
- ⁴ Lebofsky, S., Ting, E., Trinh, K. V., Nguyen, N. T., "Optimization for Load Alleviation of Truss-Braced Wing Aircraft With Variable Camber Continuous Trailing Edge Flap," 33rd AIAA Applied Aerodynamics Conference, AIAA-2015-2723, June 2015.
- ⁵ Ting, E., Chaparro D., Nguyen, N. T., Fujiwara, G. E., "Optimization of Variable-Camber Continuous Trailing-Edge Flap Configuration for Drag Reduction," Journal of Aircraft, Vol. 55, No. 6, pp. 2217-2239, 2018.
- ⁶ Bartels, R. E., Stanford B. K., Waite, J. M., "Performance Enhancement of the Flexible Transonic Truss-Braced Wing Aircraft Using Variable-Camber Continuous Trailing-Edge Flaps," AIAA 2019-0316, June 17-21, 2019, Dallas, Texas
- ⁷ Vassberg, J., Dehaan M., Rivers, M., and Wahls, R., "Development of a Common Research Model for Applied CFD Validation Studies," 26th AIAA Applied Aerodynamics Conference, AIAA-2008-6919, August 2008.
- ⁸ Xiong, J., Nguyen, N., Standford, B. and Bartels, R. B., "Aeroelastic Modeling and CFD Simulation of Wind-Tunnel Scale Aspect Ratio 13.5 Common Research Model," AIAA Aviation Conference, AIAA-2021-2527, July 2021.
- ⁹ Chwalowski, P., Quon, E. and Brynildsen, S. E., "Computational Analysis of the Transonic Dynamics Tunnel Using FUN3D," AIAA Science and Technology Forum and Exposition, AIAA-2016-1775, January 2016.
- ¹⁰ Biedron, R. T., et al., "FUN3D Manual 13.2," NASA TM-2017-219661, Aug. 2017
- ¹¹ 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.
- ¹² Roe, P. L., "Approximate Riemann Solvers, Parameter Vectors and Difference Schemes," Journal of Computational Physics, Vol. 46, No. 2, 1980, pp. 357-378
- ¹³ 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
- ¹⁴ 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.

- ¹⁵ Fujiwara, G., Chaparro, D., and Nguyen, N., “An Integral Boundary Layer Direct Method Applied to 2D Transonic Small-Disturbance Equations,” 34th AIAA Applied Aerodynamics Conference, AIAA-2016-3160, June 2016.
- ¹⁶ Chaparro, D., Fujiwara, G., Ting, E., and Nguyen, N., “Aerodynamic Modeling of Transonic Aircraft Using Vortex Lattice Coupled with Transonic Small Disturbance for Conceptual Design,” 34th AIAA Applied Aerodynamics Conference, AIAA-2016-3012, June 2016.
- ¹⁷ Chaparro, D., Fujiwara, G. E., Ting, E., and Nguyen, N. T., “Transonic and Viscous Potential Flow Method Applied to Flexible Wing Transport Aircraft,” 35th AIAA Applied Aerodynamics Conference, AIAA-2017-4221, June 2017.