

Steady and Unsteady Simulations of Transonic Truss-Braced Wing Aircraft for Flight Dynamic Stability Analysis

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This paper presents steady and unsteady simulations of the Mach 0.8 and Mach 0.745 Transonic Truss-Braced Wing (TTBW) aircrafts using the high-fidelity CFD solver FUN3D for the flight dynamic stability analysis. The steady-state stability derivatives with respect to the angle of attack, angle of sideslip, and airspeed are calculated with perturbations in the angle of attack, angle of sideslip, and Mach number, respectively. A series of unsteady CFD simulations is conducted for the TTBW aircrafts in pitch oscillation at various reduced frequencies. The dynamic stability derivatives are estimated using a frequency domain estimation method. The results are then compared to the results obtained from the VSPAERO stability analysis.

I. Introduction

The Subsonic Ultra Green Aircraft Research (SUGAR) Transonic Truss-Braced Wing (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 Mach 0.8 Transonic Truss-Braced Wing (TTBW) aircraft shown in Figure 1 is designed to be aerodynamically efficient by employing an aspect ratio of about 19.55, which is significantly greater than those of conventional aircraft cantilever wings. The main idea is to use truss structures to alleviate the wing root bending moment, so that a significant increase in the wing aspect ratio could be afforded. The design of a truss-braced wing is a Multidisciplinary Design Analysis and Optimization (MDAO) process that strives to achieve a delicate balance between aerodynamic and structural efficiencies. A typical MDAO process uses a variety of different tools of varying fidelity for many different purposes such as aerodynamic prediction, aero-structural analysis, flutter analysis. Computational Fluid Dynamics (CFD) is the main tool for aerodynamic prediction.

Vehicle stability analysis is an important study to determine both static and dynamic stability of flight vehicles. A set of linearized flight dynamic equations of motion are established to predict the vehicle stability and its motion under applied aerodynamic forces and moments generated by flight control surfaces. Static stability of an aircraft depends on steady state stability derivatives. Dynamic stability depends on a larger set of stability derivatives which include both steady state and dynamic stability derivatives. The partial derivatives of the aerodynamic coefficients with respect to the dynamic states of the aircraft are usually called dynamic stability derivatives. The steady state stability derivatives with respect to the angular rates generally can be computed by various analytical techniques. On the other hand, dynamic stability derivatives with respect to the aircraft states and their time derivatives are more difficult to establish as these derivatives are generally frequency dependent. The frequency dependency manifests itself as a time delay in the aerodynamic response of the aircraft which can be important. The steady state and dynamic stability derivatives can be estimated experimentally by stability-and-control (S&C) forced oscillation wind tunnel experiments or analytically by unsteady flow simulations.

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

In this paper a series of steady and unsteady simulations of the Mach 0.8 and Mach 0.745 TTBW aircrafts are conducted using the high-fidelity CFD solver FUN3D for the flight dynamic stability analysis. The steady-state stability derivatives with respect to the angle of attack, angle of sideslip, and airspeed are calculated with perturbations in the angle of attack, angle of sideslip, and Mach number, respectively. A series of unsteady CFD simulations is conducted for the TTBW aircrafts in pitch oscillation at various reduced frequencies. The dynamic stability derivatives are estimated using a frequency domain estimation method.⁴ The results are then compared to the results obtained from the VSPAERO stability analysis.

II. Computational Approach

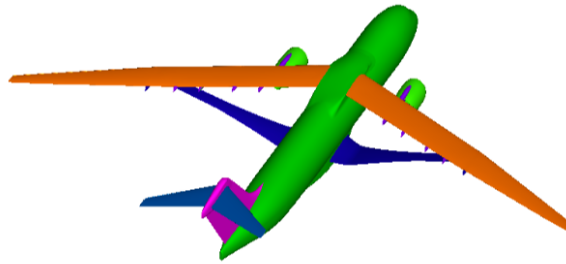
A. Numerical Code

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.

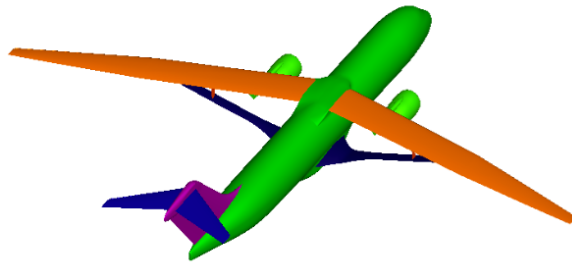
B. Computational Model and Grid

In this paper, the 1g cruise shape geometries of the Mach 0.8 and Mach 0.745 TTBW aircraft are used in the study. Figure 2 illustrates the Mach 0.8 and Mach 0.745 TTBW geometries.

Figure 12 shows the surface meshes of the geometries. The volume meshes are comprised of tetrahedral elements and a prism layer near the wall. The mesh sizes are about 192 million and 180 million nodes for the Mach 0.8 and Mach 0.745 TTBW full model, respectively. The prism layer is used to resolve the turbulent boundary layer. The y^+ of the first cell from the wall is less than 1.



(a) Mach 0.8 TTBW

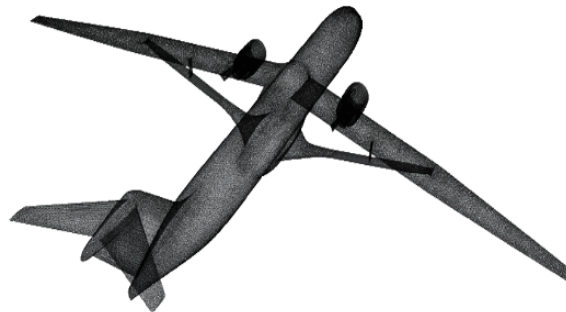


(b) Mach 0.745 TTBW

Figure 2 TTBW Aircraft Geometries.



(a) Mach 0.8 TTBW



(b) Mach 0.745 TTBW

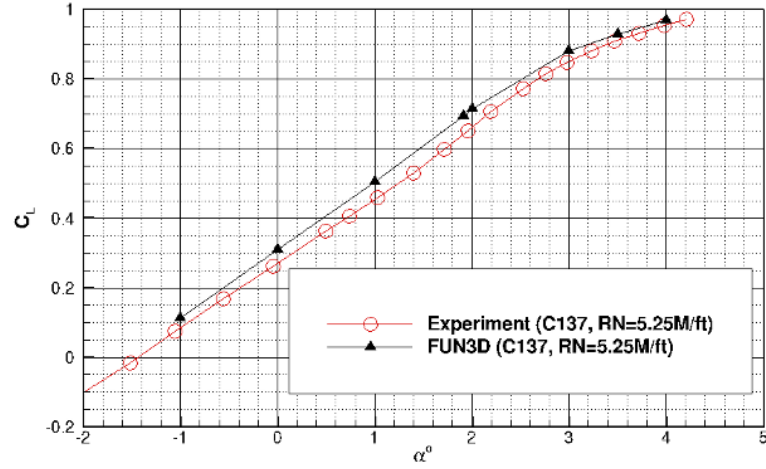
Figure 3 TTBW Aircraft CFD Meshes.

III. Results

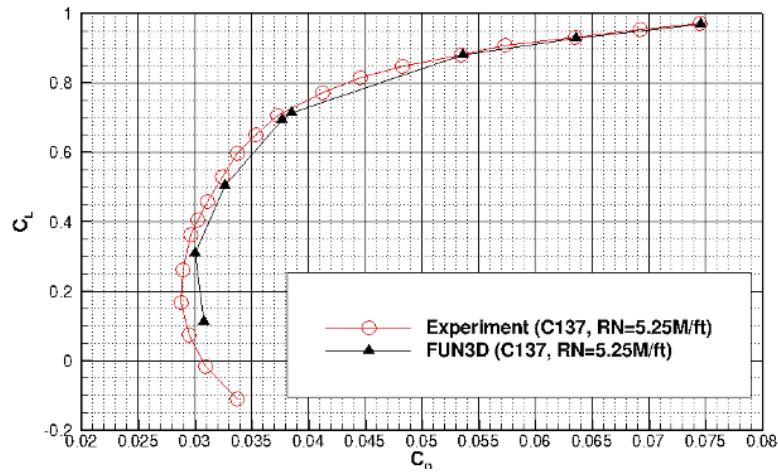
The computation results are validated with the experimental data for the Mach 0.8 TTBW geometry tested configuration, config-137 which does not include the horizontal tail and jury strut. Wind tunnel test data of the Mach 0.8 TTBW model in NASA Ames 11-Ft Transonic Wind Tunnel are available for validation. Test data from Run 378 at Mach 0.8 and Reynolds number of 2.17 million based on the mean aerodynamic chord (MAC) with full wind tunnel model corrections are used for the config-137 validation. After the validation, FUN3D code is used to perform the steady and unsteady simulations at flight condition for the flight dynamic stability analysis. The same computation procedures are applied to the Mach 0.745 TTBW for which the wind tunnel data are also available.

A. CFD Solver Validation

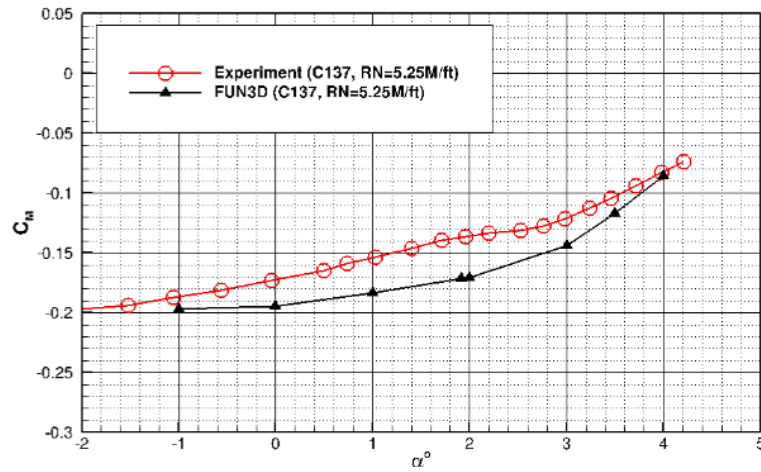
The presentation of the results begins with a comparison between the aerodynamic forces and moment coefficients obtained both experimentally from a wind tunnel test in the NASA Ames 11-By-11-Foot Transonic Wind Tunnel, and computationally via FUN3D for the Mach 0.8 TTBW geometry config-137 for Mach 0.8 and a Reynolds number of 2.17 million. Figure 18 shows the lift, drag, and pitching moment coefficients computed by FUN3D as well as Run 378 wind tunnel data. Compared to the experimental data, FUN3D slightly overpredicts the lift and moment coefficient. There is an angle of attack shift of approximately 0.23 degrees at the design lift coefficient of 0.695. The drag polar computed by FUN3D shows good agreement with the wind tunnel data. The difference in the drag coefficient at the design lift coefficient of 0.695 is about 8 counts. The discrepancy in the drag coefficient progressively becomes larger at lower lift coefficients. FUN3D overpredicts the pitch moment coefficient. Figure 5 shows the surface pressure coefficient distribution at one simulated flight condition of config-137. There is a weak shock structure on the wing, which helps to improve the lift coefficient with a small drag penalty at transonic conditions. The close agreements with wind tunnel data provide confidence in the FUN3D prediction for further investigating the flight dynamics. Similar validation of the Mach 0.745 TTBW geometry has been performed.¹⁰ The FUN3D results are shown to be in very good agreement with the wind tunnel data.



(a) Lift Curve



(b) Drag Polar



(c) Pitch Moment Curve

Figure 4 Comparison of Lift, Drag, and Pitching Moment Predictions for the TTBW Geometry Config-137 at Mach 0.8 and $Re = 2.17 \times 10^6$.

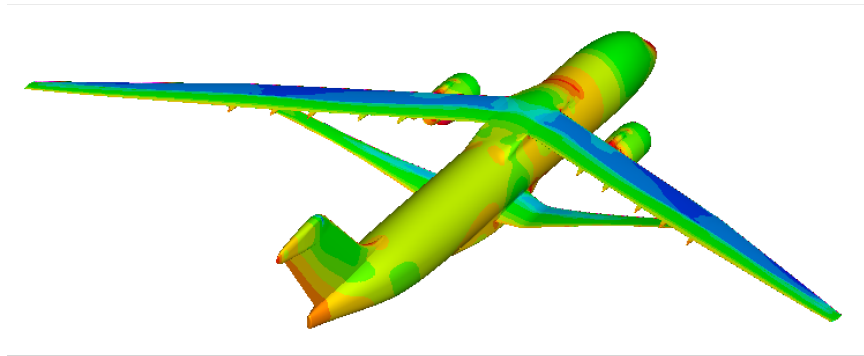
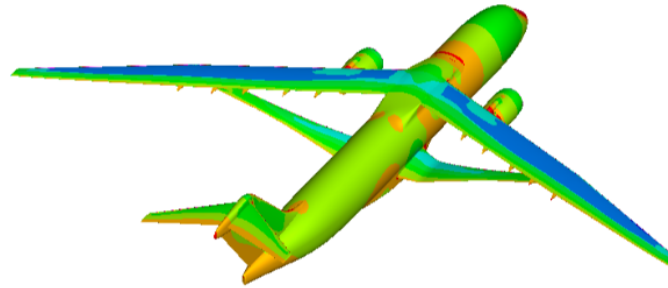


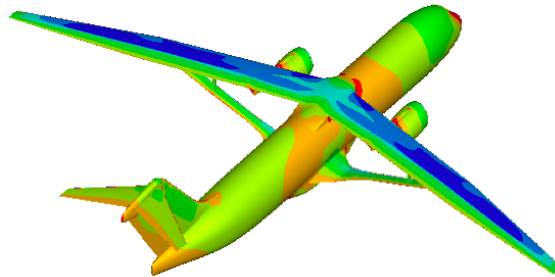
Figure 5 Pressure Coefficient Contour on the TTBW Geometry Config-137 Surface at Mach 0.8, C_L 0.695 and $Re = 2.17 \times 10^6$.

B. Steady-state Simulations

The trim solutions are obtained by iterating on the angle of attack and horizontal tail incidence angle. The altitudes for the Mach 0.8 and Mach 0.745 TTBW geometries are determined by matching the mid-cruise gross weights of 130,470 lbs and 138,000 lbs, respectively to the trim weights established by the design lift coefficients of 0.695 for the Mach 0.8 TTBW and 0.73 for the Mach 0.745 TTBW. Note that these altitudes are not in agreement with the design altitude of 40,000 ft used in aerodynamic analysis. The discrepancies between the mid-cruise gross weights and trim weights of the Mach 0.8 and 0.745 TTBW are to be resolved in the future. Figure 6 shows the pressure contours for the Mach 0.8 and Mach 0.745 TTBW at the trim conditions. The steady-state stability derivatives with respect to the angle of attack, angle of sideslip, and airspeed are calculated with perturbations in the angle of attack by ± 0.1 degrees, in the angle of sideslip by ± 0.1 degree, and in the Mach number by ± 0.005 , respectively. Figure 7-8 show the pressure contours for the Mach 0.8 and Mach 0.745 TTBW angle of attack perturbation. Figure 9-10 show the pressure contours for the Mach 0.8 and Mach 0.745 TTBW angle of sideslip perturbation. Figure 11-12 show the pressure contours for the Mach 0.8 and Mach 0.745 TTBW Mach number perturbation.

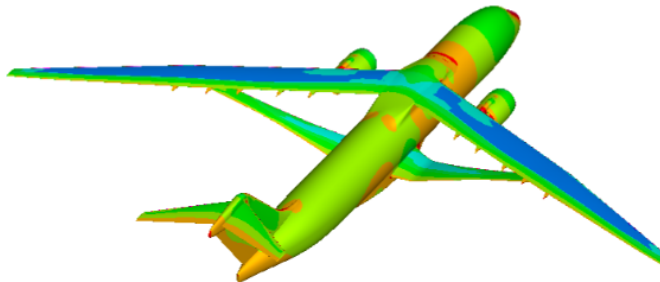


(a) Mach 0.8 TTBW

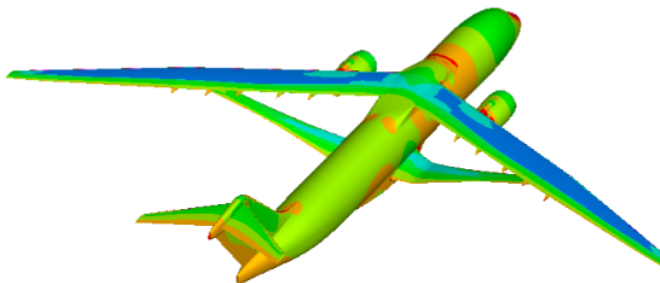


(b) Mach 0.745 TTBW

Figure 6 Pressure Coefficient Contour on the TTBW Geometries at Trim Conditions.

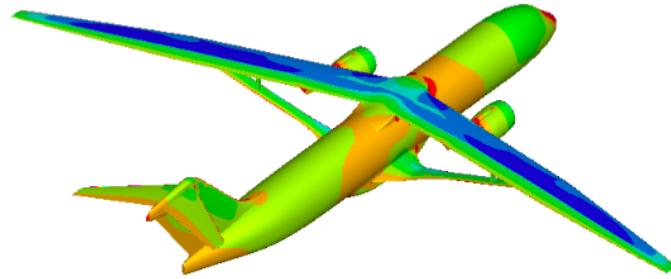


(a) $\alpha = 1.82$

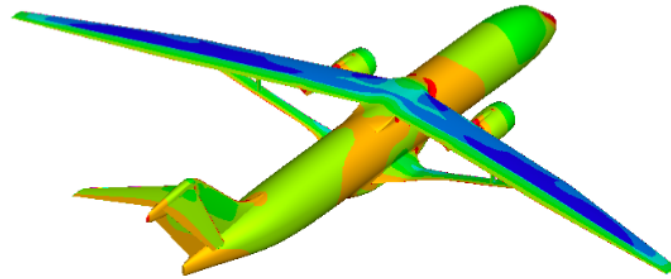


(b) $\alpha = 1.62$

Figure 7 Pressure Coefficient Contour on the Mach 0.8 TTBW for Angle of Attack Perturbation.

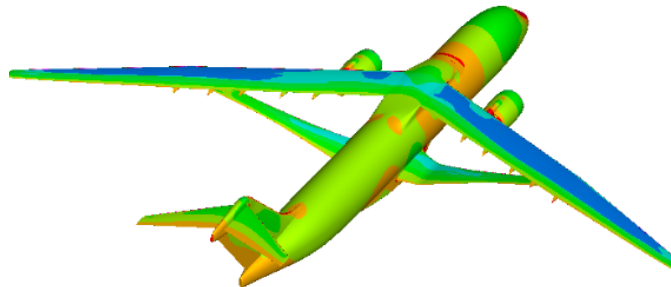


(a) $\alpha = 2.12$

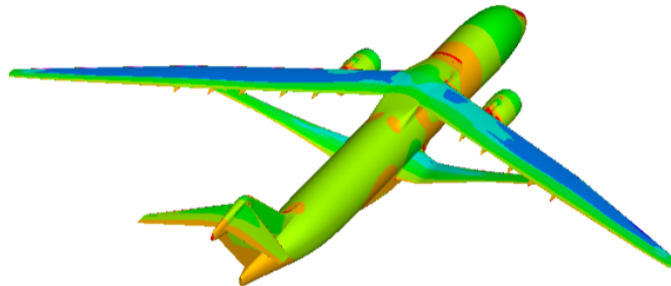


(b) $\alpha = 1.92$

Figure 8 Pressure Coefficient Contour on the Mach 0.745 TTBW for Angle of Attack Perturbation.

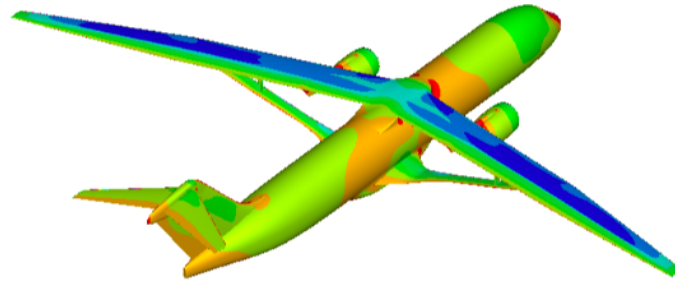


(a) $\beta = 0.1$

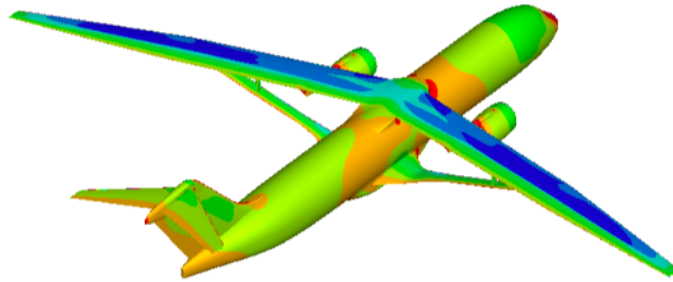


(b) $\beta = -0.1$

Figure 9 Pressure Coefficient Contour on the Mach 0.8 TTBW for Angle of Sideslip Perturbation.

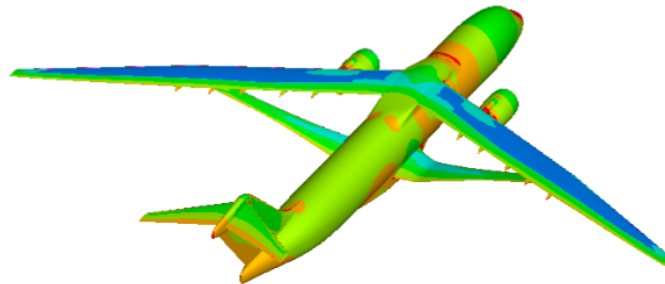


(a) $\beta = 0.1$

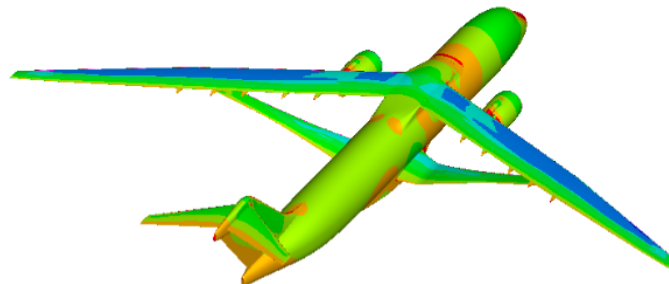


(b) $\beta = -0.1$

Figure 10 Pressure Coefficient Contour on the Mach 0.745 TTBW for Angle of Sideslip Perturbation.



(a) Mach = 0.805



(b) Mach = 0.795

Figure 11 Pressure Coefficient Contour on the Mach 0.8 TTBW for Mach number Perturbation.

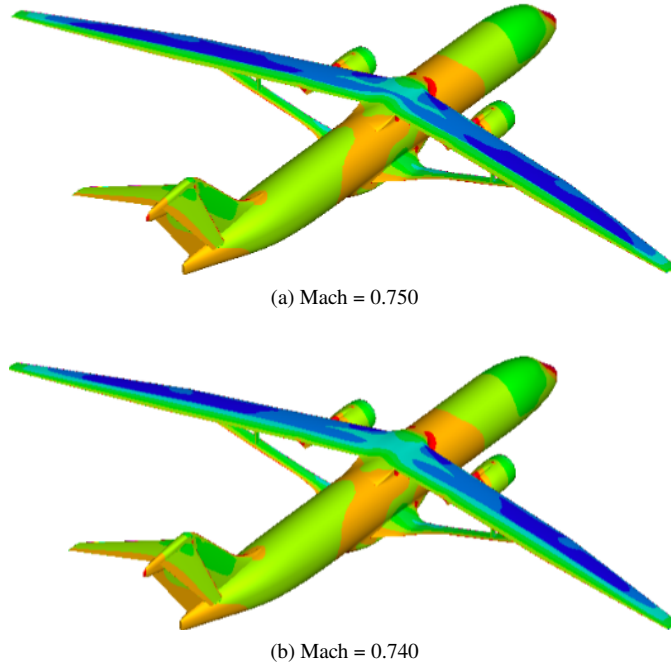


Figure 12 Pressure Coefficient Contour on the Mach 0.745 TTBW for Mach number Perturbation.

The steady-state derivatives are then compared to the results obtained from the VSPAERO model stability analysis. The VSPAERO model¹¹ includes the TSD/IBL transonic and boundary layer corrections to account for wave drag and viscous drag. Table 7 - Table 6 show the comparison of the steady-state derivatives with respect to the angle of attack, angle of sideslip, and airspeed obtained by FUN3D and VSPAERO. The agreement among them is very good.

	Steady-State FUN3D	VSPAERO	Difference (%)
$C_{L\alpha}$	13.3577	13.2762	0.61
$C_{D\alpha}$	0.5273	0.5209	1.21
$C_{m\alpha}$	-3.6312	-3.6751	1.21

Table 1 Comparison of the Mach 0.8 TTBW Steady-State Stability Derivatives with Respect to Angle of Attack

	Steady-State FUN3D	VSPAERO	Difference (%)
$C_{L\alpha}$	11.4301	11.3617	0.60
$C_{D\alpha}$	0.4284	0.4232	1.21
$C_{m\alpha}$	-6.0328	-5.9598	1.21

Table 2 Comparison of the Mach 0.745 TTBW Steady-State Stability Derivatives with Respect to Angle of Attack

	Steady-State FUN3D	VSPAERO	Difference (%)
$C_{y\beta}$	-0.6863	-0.6828	0.51
$c_{l\beta}$	-0.2108	-0.2095	0.62
$c_{n\beta}$	0.02667	0.02696	1.09

Table 3 Comparison of the Mach 0.8 TTBW Steady-State Stability Derivatives with Respect to Angle of Sideslip

	Steady-State FUN3D	VSPAERO	Difference (%)
$C_{y\beta}$	-0.9090	-0.9043	0.52
$c_{l\beta}$	-0.1121	-0.1114	0.62
$c_{n\beta}$	0.02301	0.02270	1.35

Table 4 Comparison of the Mach 0.745 TTBW Steady-State Stability Derivatives with Respect to Angle of Sideslip

	Steady-State FUN3D	VSPAERO	Difference (%)
C_{L_u}	1.5873	1.6002	0.81
C_{D_u}	0.1518	0.1475	2.83
C_{m_u}	-0.07356	-0.07474	1.60

Table 5 Comparison of the Mach 0.8 TTBW Steady-State Stability Derivatives with Respect to Airspeed

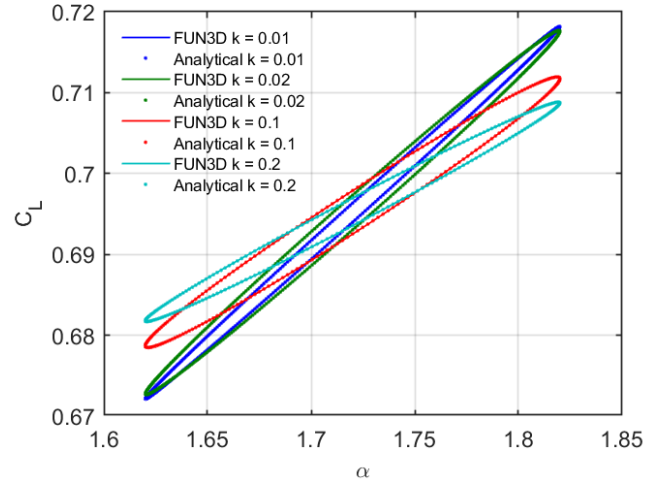
	Steady-State FUN3D	VSPAERO	Difference (%)
C_{L_u}	5.1630	5.1367	0.51
C_{D_u}	0.5404	0.5280	2.29
C_{m_u}	-0.02590	-0.02551	1.51

Table 6 Comparison of the Mach 0.745 TTBW Steady-State Stability Derivatives with Respect to Airspeed

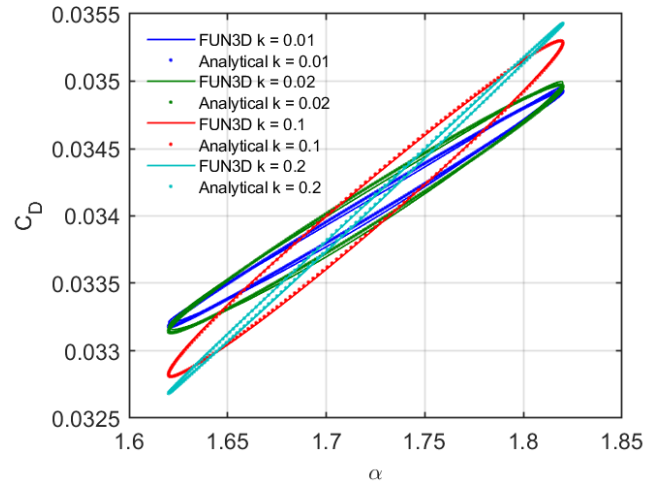
C. Unsteady Simulations and Frequency-Domain Formulation

A series of unsteady CFD simulations is conducted for the Mach 0.8 and Mach 0.745 TTBW aircrafts in pitch oscillation at various reduced frequencies $k = (\omega \bar{c}) / (2V_\infty)$. The dynamic stability derivatives are estimated using a frequency domain estimation method.⁴ In this method, the time-domain data are transformed into the frequency-domain data by Fourier series. Transfer functions of the dynamic stability derivatives are then estimated by a frequency-domain regression. The form of the transfer functions is designed to provide the estimation of the various contributions of the steady-state and dynamic stability derivatives. The results are then compared to the results obtained from the FUN3D and VSPAERO steady-state stability analysis.

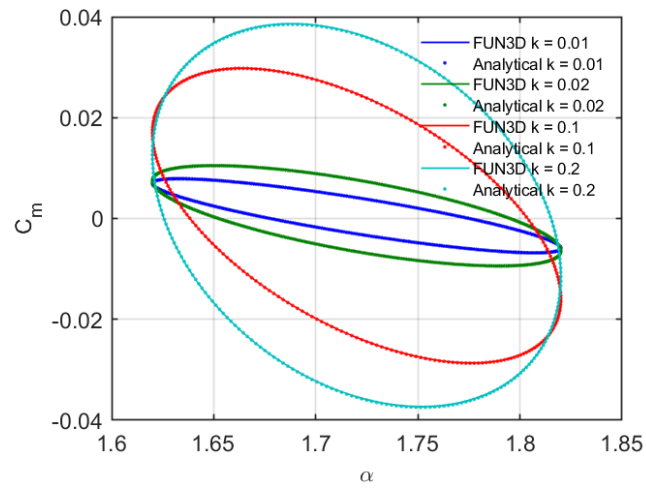
Figure 13-15 presents the lift, drag, and pitching moment coefficients against the pitch angle of attack for the unsteady pitch oscillation for the Mach 0.8 TTBW aircraft with the reduced frequency 0.01, 0.02, 0.1 and 0.2. Figure 16-18 presents the lift, drag, and pitching moment coefficients against the pitch angle of attack for the unsteady pitch oscillation for the Mach 0.745TTBW aircraft with the reduced frequency 0.01, 0.02, 0.1 and 0.2.



(a) Lift Coefficient

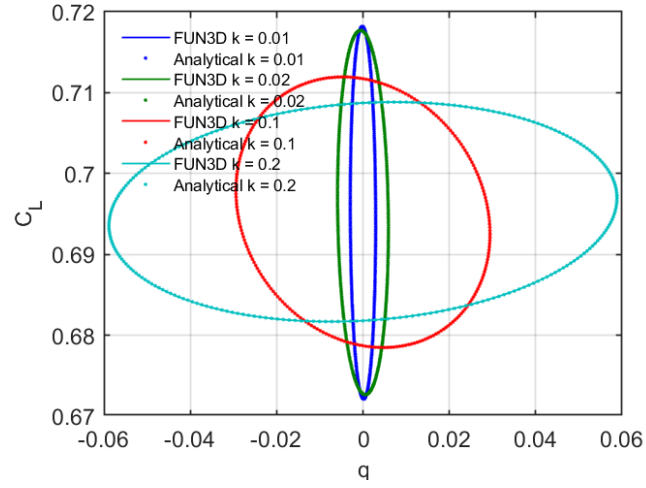


(b) Drag Coefficient

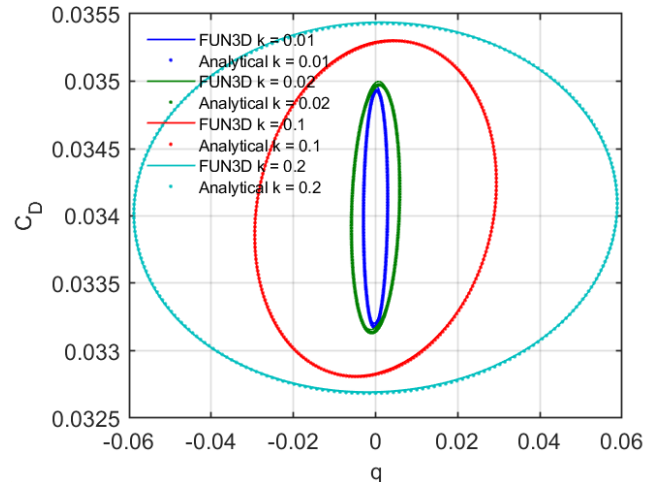


(c) Pitch Moment Coefficient

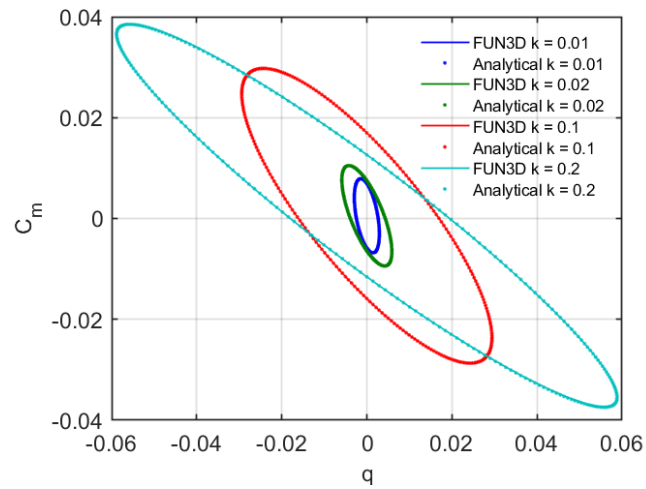
Figure 13 Pitch Oscillation Aerodynamics vs Pitch Angle for the Mach 0.8 TTBW.



(a) Lift Coefficient

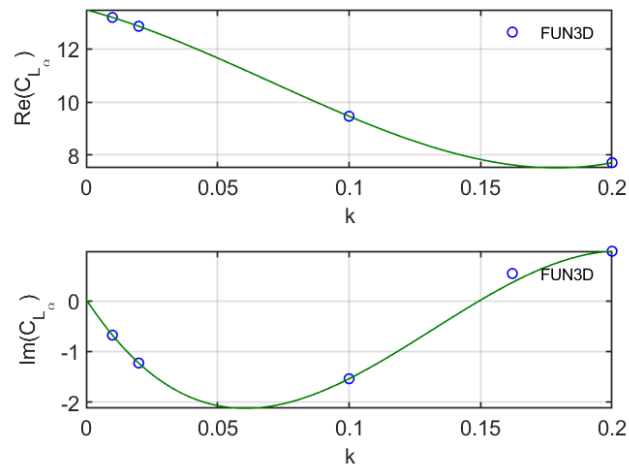


(b) Drag Coefficient

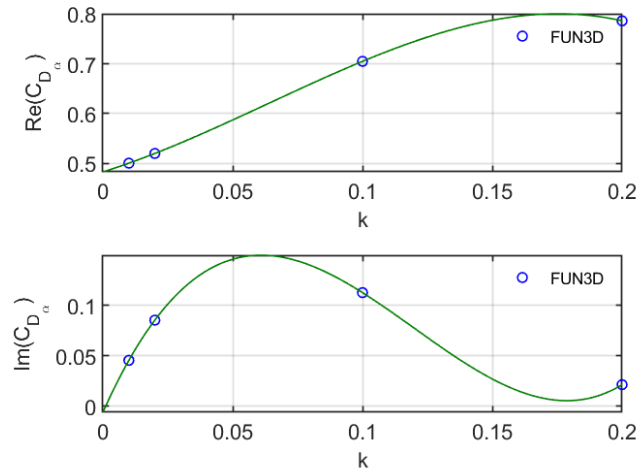


(c) Pitch Moment Coefficient

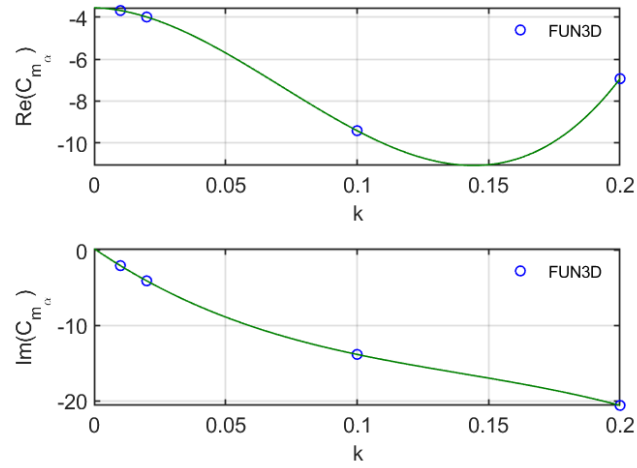
Figure 14 Pitch Oscillation Aerodynamics vs Pitch Rate for the Mach 0.8 TTBW.



(a) Lift Coefficient

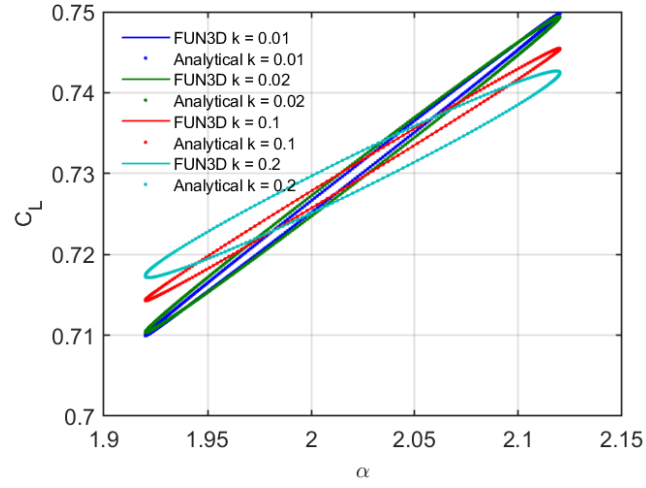


(b) Drag Coefficient

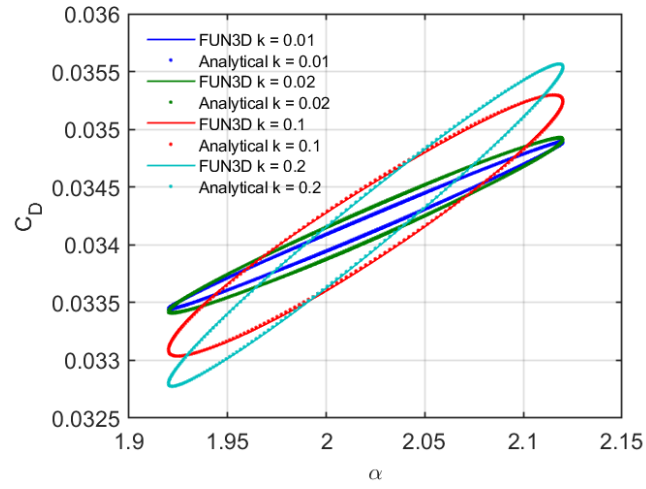


(c) Pitch Moment Coefficient

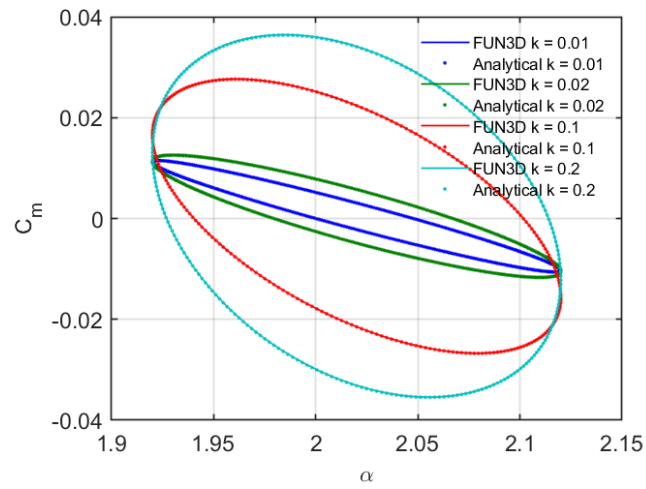
Figure 15 Pitch Oscillation Aerodynamics vs Reduced Frequency for the Mach 0.8 TTBW.



(a) Lift Coefficient

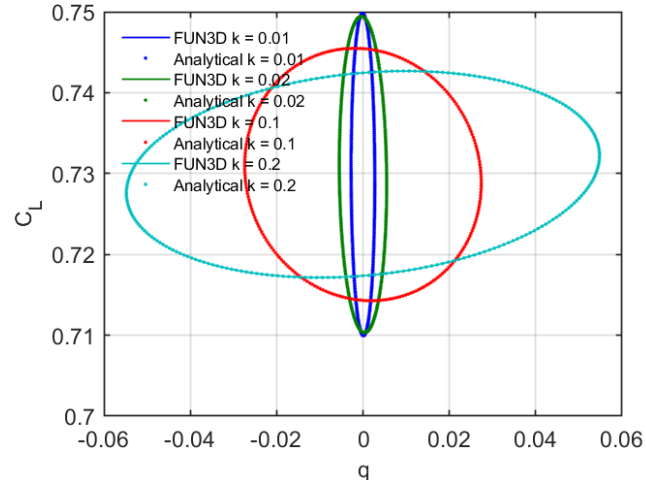


(b) Drag Coefficient

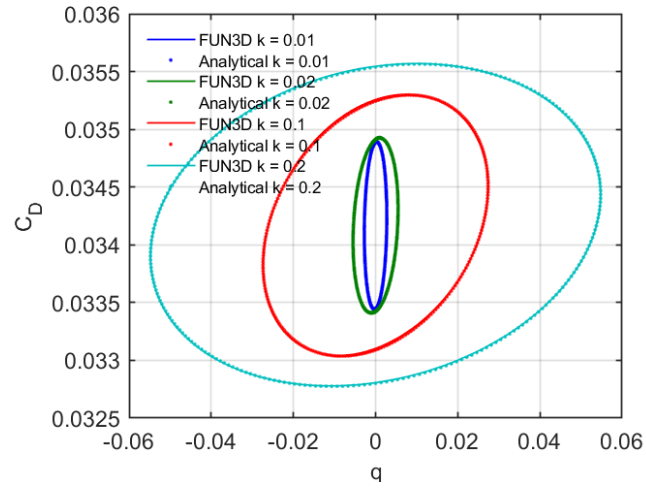


(c) Pitch Moment Coefficient

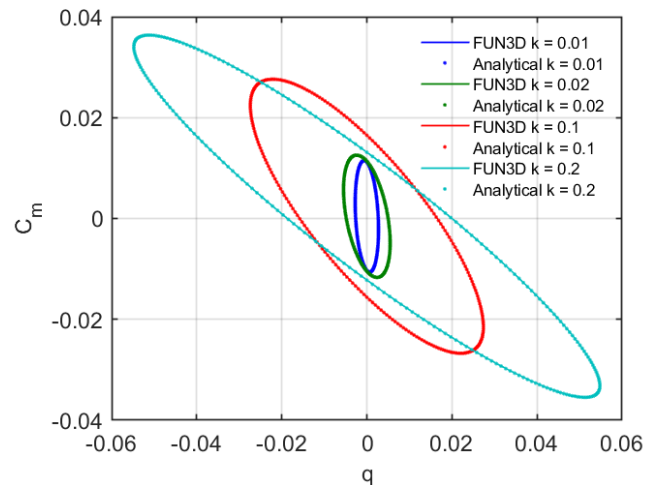
Figure 16 Pitch Oscillation Aerodynamics vs Pitch Angle for the Mach 0.745 TTBW.



(a) Lift Coefficient

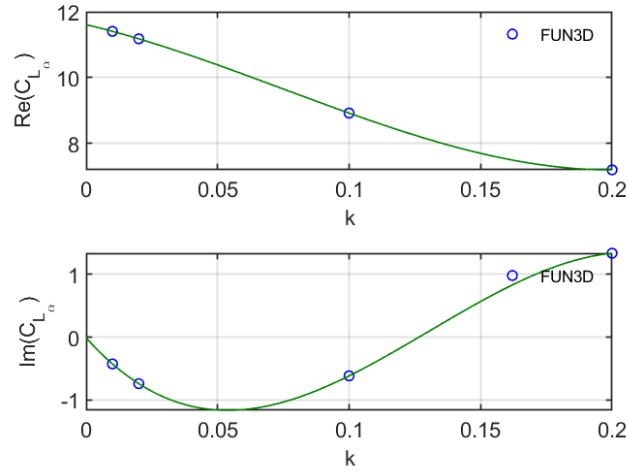


(b) Drag Coefficient

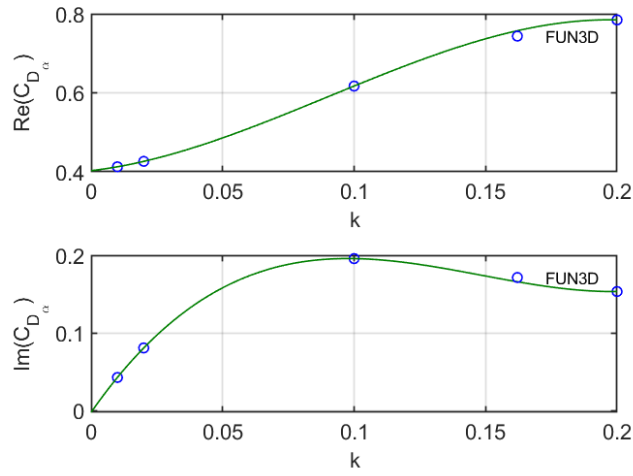


(c) Pitch Moment Coefficient

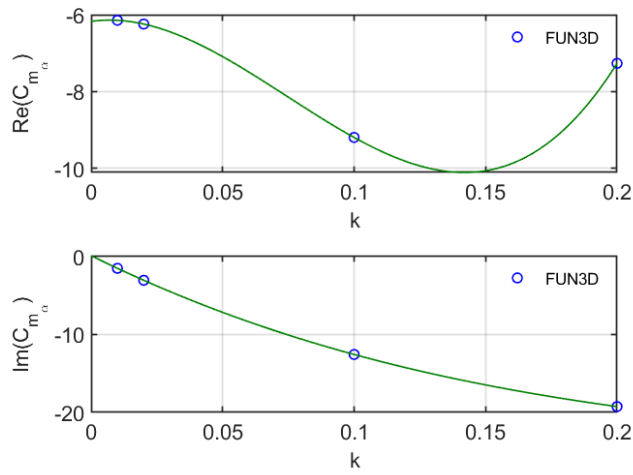
Figure 17 Pitch Oscillation Aerodynamics vs Pitch Rate for the Mach 0.745 TTBW.



(a) Lift Coefficient



(b) Drag Coefficient



(c) Pitch Moment Coefficient

Figure 18 Pitch Oscillation Aerodynamics vs Reduced Frequency for the Mach 0.745 TTBW.

Table 7 - Table 6 show the comparison of the steady-state derivatives with respect to the angle of attack obtained by FUN3D and VSPAERO. The agreement among them is very good.

In order to estimate the dynamic stability derivative with respect to the pitch rate the contribution by the angle of attack must be subtracted from the aerodynamic coefficients. This requires performing a series of plunge simulations to isolate the angular of attack contributions to the aerodynamic coefficients. Then the differences in the aerodynamic coefficients between the pitch and plunge oscillations are used to estimate the dynamic stability derivatives with respect to the pitch rate.⁴

	Unsteady FUN3D	Steady-State FUN3D	VSPAERO
C_{L_α}	13.4427	13.3577	13.2762
C_{D_α}	0.4832	0.5273	0.5209
C_{m_α}	-3.5403	-3.6312	-3.6751

Table 7 Comparison of the Mach 0.8 TTBW Steady-State Stability Derivatives with Respect to Angle of Attack

	Unsteady FUN3D	Steady-State FUN3D	VSPAERO
C_{L_α}	11.5890	11.4301	11.3617
C_{D_α}	0.4030	0.4284	0.4232
C_{m_α}	-6.1642	-6.0328	-5.9598

Table 8 Comparison of the Mach 0.745 TTBW Steady-State Stability Derivatives with Respect to Angle of Attack

Conclusions

In this paper the steady and unsteady simulations of the Mach 0.8 and Mach 0.745 TTBW aircraft using the high-fidelity CFD solver FUN3D are conducted for the flight dynamic stability analysis. The steady-state stability derivatives with respect to the angle of attack, angle of sideslip, and airspeed are calculated with perturbations in the angle of attack, angle of sideslip, and Mach number, respectively. A series of unsteady CFD simulations is conducted for the Mach 0.8 and Mach 0.745 TTBW aircrafts in pitch oscillation at various reduced frequencies. The dynamic stability derivatives are estimated using a frequency domain estimation method. The comparisons of the steady-state derivatives obtained by unsteady FUN3D simulation, steady FUN3D, and VSPAERO are very good.

Acknowledgment

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