

Computational Analysis of X-57 Rate Derivatives and Comparison to Wind-Tunnel Data

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Rate derivatives of the X-57 wind-tunnel model were evaluated using hysteresis data from computational fluid dynamics (CFD) simulation, then compared with that which was computed using the wind-tunnel experimental data. To accomplish the task, hysteresis data of the pitch, roll, and yaw oscillations were produced numerically using two different CFD solvers: 1) the STAR-CCM+; and 2) the Launch Ascent and Vehicle Analysis. The rate derivatives were computed using the same parameter identification technique on CFD- and wind-tunnel-based hysteresis data. Results show CFD-based pitch rate derivatives have a large error, up to 73 percent, whereas the lateral and directional derivatives compared well with errors within 5 percent with respect to the that computed using the wind-tunnel data. This result may be due to the lack of modeled apparatuses, such as wind-tunnel walls, the sting in the CFD simulation, as well as the lack of wall correction in the wind-tunnel data, which has a larger impact on pitch than lateral and directional oscillations. Geometrical features, such as the shape, slope of extremities, and enclosed area were compared between CFD- and wind-tunnel-based hysteresis. Results show that an area-enclosed by the hysteresis had the largest influence on the accuracy of the computed rate derivatives, given that shapes of the hysteresis were roughly equivalent.

I. Nomenclature

C_l, C_m, C_n = rolling, pitching, yawing moment coefficient, respectively
 C_{lp}, C_{np} = rolling, yawing moment coefficient due to roll rate, respectively
 C_{lr}, C_{nr} = rolling, yawing moment coefficient due to yaw rate, respectively
 C_{mq} = pitching moment coefficient due to pitch rate

II. Introduction

Accurate prediction of rate derivatives (a.k.a., dynamic derivatives) has been of high interest due to its importance in simulating the dynamics of the aircraft, typically used for mission preparation and pilot training. There is currently no published guideline or best practice on what must be done to accurately predict the rate derivatives. Recently, the

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American Institute of Aeronautics and Astronautics (AIAA) started a Stability and Control Prediction Workshop [1], sponsored by the applied Aerodynamics and Atmospheric Flight Mechanics Technical Committees, to focus efforts of accurately predicting both static and rate derivatives to address this issue. The workshop shows potential to produce high-quality results; however, the workshop is still in its infancy and no guideline has been published to date.

The process of computing the rate derivative is relatively straight forward. First, a hysteresis response in the interested axis (pitch, roll, or yaw) is obtained through numerical simulation or wind-tunnel experiments. The parameter identification algorithm is then applied to the hysteresis response to compute the rate derivative. A wind-tunnel-based hysteresis response is desired; however, often difficult to obtain due to cost involved in wind-tunnel tests. As such, computational fluid dynamics (CFD) simulations are used to generate the hysteresis response. Based on the method described, the accuracy of the computed rate derivative largely depends on the quality and accuracy of the hysteresis response.

This paper presents the rate derivatives of the X-57 Mod-III [2] wind-tunnel model, which was computed using hysteresis from both CFD simulations and wind-tunnel experiments. The wind-tunnel experiments were conducted using the 12-Foot Low-Speed Tunnel (Building 644) at the National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) (Hampton, Virginia). The CFD simulations were conducted by two separate groups: 1) the Aerodynamics and Propulsion Branch (Code 520, Flow Physics Group) at NASA Armstrong Flight Research Center (AFRC) (Edwards, California), using a commercially available STAR-CCM+ CFD package; and 2) the Computational Aerosciences Branch at NASA Ames Research Center (ARC) (Moffett Field, California), using the in-house developed Launch Ascent and Vehicle Analysis (LAVA) solver. There were two objectives to this study: the first, compare the accuracy of CFD-based rate derivatives relative to those based on the wind-tunnel experiments and validate currently used best practices in CFD simulations; the second, compare the hysteresis from CFD simulations and wind-tunnel experiments, and determine possible factors that contributed to the accuracy of the computed rate derivatives. Several characteristics of the hysteresis, such as the shape, enclosed area, and slope of the angle-of-attack extremities were evaluated.

The following sections present details of the aircraft, CFD methodology, and results. Four cases were evaluated: two cases in pitch (low and high angle of attack); one case in roll; and one case in yaw.

III. Aircraft Geometry

The wind-tunnel model at 19 percent scale of the X-57 Mod-III aircraft [2] was utilized in the simulations. All control surfaces and flaps were set to neutral position and propellers were excluded from the model. The geometric reference parameters are tabulated in Table 1. The atmospheric condition was defined to that of sea level at Mach 0.052 to match the wind-tunnel experimental condition. The atmospheric values are tabulated in Table 2. To obtain the hysteresis response for rate derivative analysis, the aircraft was oscillated sinusoidally about each individual axis in the body-axis coordinate system of the aircraft, centered about the moment reference center (MRC) of the aircraft. The body axis is a right-handed coordinate system oriented such that x axis is directed tail to nose, y axis is pointed toward the tip of the right wing, and z axis is pointed down. Figure 1 depicts the aircraft modeled in the simulation with the body axis centered at the MRC.

Table 1 Geometric reference parameters.

Parameter	Value	Unit
Mean aerodynamic chord	0.1221	m
Wingspan	1.8312	m
Wing reference area	0.2236	m ²
Moment reference center with respect to nose	(0.6602, 0.0, 0.0575)	m

Table 2 Atmospheric condition.

Parameter	Value	Unit
Mach	0.052	
Speed of sound	340.3	m/s
Density	1.225	kg/m ³
Static pressure	101325	N/m ²
Static temperature	288.2	K
Coefficient of viscosity	1.79E-05	kg/(m*s)
velocity	17.6956	m/s

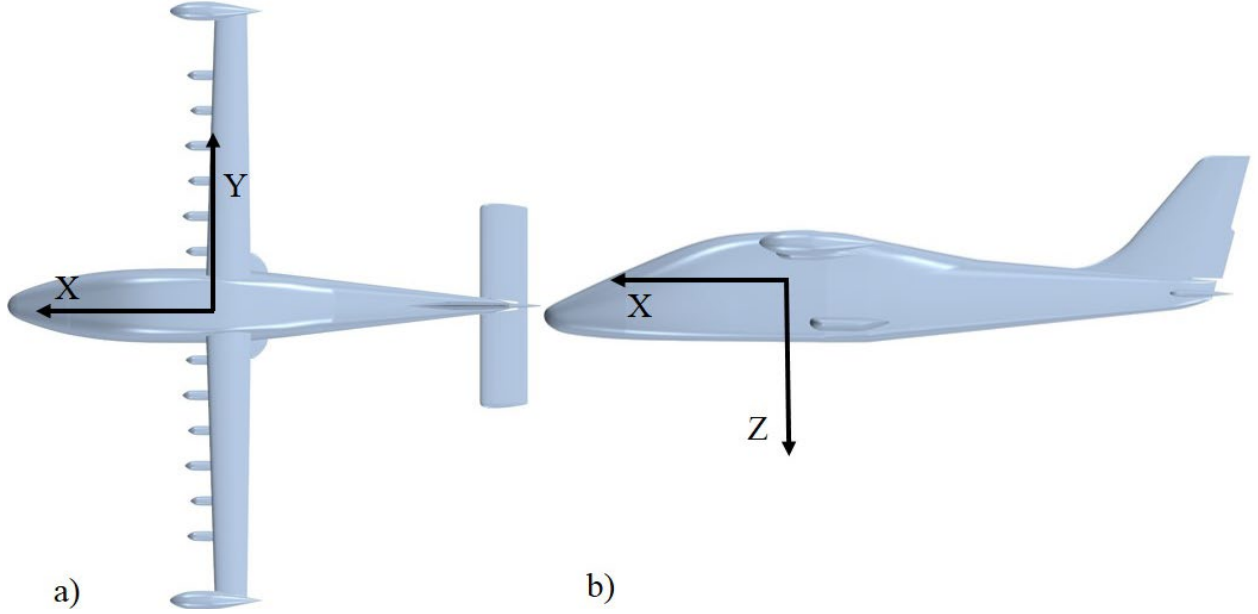


Fig. 1 a) The X-57 model with the body-axis coordinate system (top view); and b) origin at MRC (left-side view).

IV. Computational Method and Simulation Setup

This paper presents results from two NASA Centers, AFRC and ARC, which collaborated using two different CFD solvers and grid topologies. The AFRC utilized a commercially available CFD package STAR-CCM+ [3] SIEMENS software (Siemens Industry Software Inc., Plano, Texas) to contribute to the studies presented in this paper. It is a comprehensive suite of CFD tools that has been validated and utilized extensively at NASA AFRC. The NASA ARC participated in the study using the in-house developed Launch Ascent Vehicle Analysis (LAVA) [4] with its structured, curvilinear, overset solver - a solver that has also been extensively utilized and validated.

A. STAR-CCM+

The STAR-CCM+ [3] is a comprehensive CFD simulation software package consisting of geometry manipulation tools, mesh generators, flow solvers, and post processing tools. The STAR-CCM+ flow solver used in this study solves the compressible Reynolds-Averaged Navier-Stokes (RAN) equation in a finite-volume, cell-centered formulation. The flow was assumed fully turbulent, resolved using the one-equation Spalart-Allmaras [5] turbulence model with rotational correction [6] and quadratic constitutive relation [7]. The inviscid fluxes were discretized using the Weiss-Smith preconditioned second-order Roe flux-differencing scheme [8, 9]. The algebraic multigrid linear solver using the Gauss-Seidel relaxation scheme was used to solve the system of linear equations. The variable gradients were computed using the hybrid Gauss least-squares method and limited using the Venkatakrishnan scheme [10]. The low

Mach preconditioner [11] was not utilized. The computational mesh used in the STAR-CCM+ simulations were created using the unstructured polyhedral mesh generator combined with an advancing layer mesh generator for the prism mesh.

The computational mesh was created using the best practices established in work published by Duensing [12]. A half-span model of the aircraft was modeled using the symmetry plane boundary condition for pitch oscillation simulation, whereas the full-span model was used for the roll and yaw oscillation simulations. Although the wind-tunnel model was simulated, wind-tunnel apparatuses such as the sting and tunnel walls were not modeled in the simulation. The far field was defined as 50 span lengths of the aircraft and was modeled using the characteristic far-field boundary condition. The resulting volume mesh consists of approximately 42 million cells on the half-span model and 84 million cells on the full-span model. A representative surface mesh used in STAR-CCM+ is shown in Fig. 2.

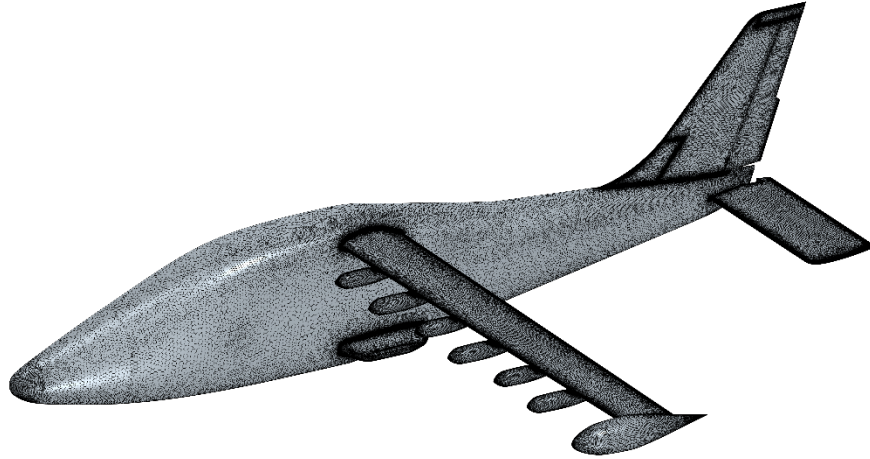


Fig. 2 Representative surface mesh used in STAR-CCM+.

B. LAVA

While AFRC used a commercial CFD package, ARC used an in-house developed Launch Ascent and Vehicle Analysis (LAVA) [4] framework-structured curvilinear flow solver that solves the compressible Reynolds-Averaged Navier-Stokes equation in finite difference formulation. The flow was assumed fully turbulent using the one-equation Spalart-Allmaras turbulence model [5] with rotational correction [6] and quadratic constitutive relation [7]. A second-order modified Roe scheme [13, 14] with the van Albada slope limiter was used to discretize the convective flux. The low Mach preconditioner [10] was used. The computational domain was discretized using the structured overset grid topology. The full-span aircraft was modeled for all simulation. As with STAR-CCM+ analysis, wind-tunnel apparatuses, such as the sting and tunnel walls were not included in the model.

The computational mesh used in the simulations were created using the body-fitted, structured, curvilinear overset mesh topology that is known for its high-quality and computational efficiency. The topology also allows for ease and rapid generation and modification of the mesh to accommodate for configuration changes. The meshes were created following the current best practice with respect to grid spacing, stretching ratio, y^+ value, and grid-quality metrics, as specified by the “3rd AIAA High Lift Prediction Workshop” [15]. The details of the mesh generations are published by Duensing [11]. Structured surface meshes were created using Pointwise [16] and Chimera Grid Tools (CGT) [17] software packages. The body-fitted near-body volume meshes were generated using a hyperbolic mesh generator within CGT, marching away from the surface mesh. Off-body Cartesian meshes were also created around each major component of the aircraft to serve as an interface between the body-fitted near-body volume mesh and far-field Cartesian mesh. The far-field distance was set to 1,000 body lengths away from the aircraft. The resulting volume mesh consisted of approximately 130 million points. A representative surface mesh, taken from Duensing [12] is shown in Fig. 3.

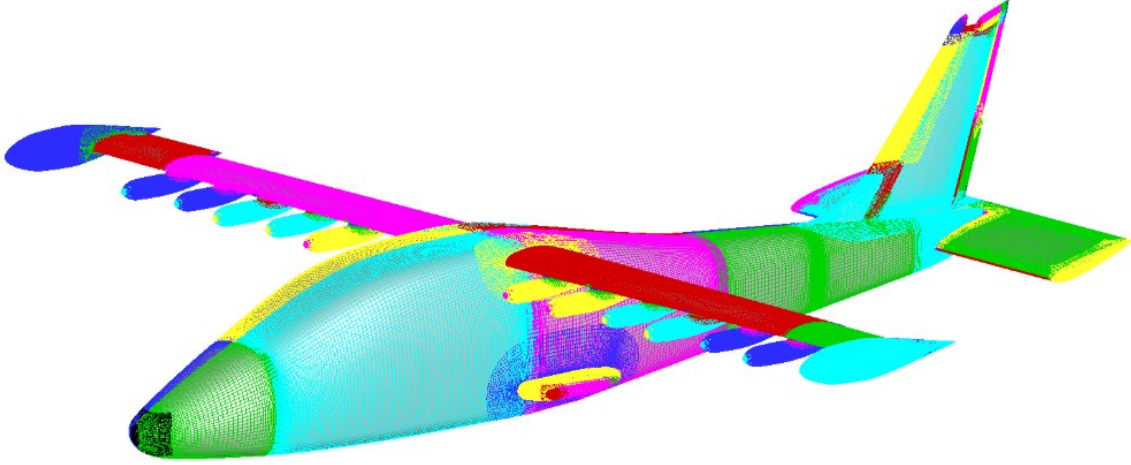


Fig. 3 Representative surface mesh used in LAVA [12].

C. Unsteady Simulation Setup

Unsteady simulations are computationally expensive compared to the steady-state simulations because the solution requires convergence in both space and time domain. To reduce the computational cost, simulations were divided into two stages: 1) steady-state simulation stage; and 2) unsteady simulation stage. In the first stage, simulations were conducted assuming steady-state flow with the aircraft positioned at the initial orientation. The steady-state simulations were conducted using a first-order scheme in time. Once the steady-state simulation converged, the second stage of the simulation started using the steady-state solution as the initial condition with the aircraft sinusoidally oscillating about the axis of interest. The unsteady simulations were conducted using a second-order dual-time stepping scheme. The STAR-CCM+ software used five sub-iterations, whereas LAVA used 10 sub-iterations. Both solvers used a physical time step of 0.0014 s. Because no relative motion was required, the entire grid system was rotated for both solvers. All simulations were converged in a temporal domain such that the hysteresis response repeated itself for at least four cycles. In spatial domain, the sub-iterations showed at least a two-order magnitude drop in a residual per time step.

A total of four simulations, tabulated in Table 3, were conducted: one low angle of attack pitch oscillation, one high angle of attack pitch oscillation, one roll oscillation, and one yaw oscillation. For each time response, results were obtained by oscillating the aircraft using sinusoidal function, as shown in Eq. (1). The variable A is the oscillation amplitude, k is the forcing frequency in cycles per second, and t is time in s. The force frequency parameter and the initial orientation of the aircraft for each run are tabulated in Table 3. The cases were selected as they were deemed to be representative for general flight characteristics of the X-57 aircraft. The high angle of attack pitch case was included (Case 2) to investigate how much difference there would be between the low and high angle of attack conditions.

$$f(t) = A \times \sin(k2\pi t) \quad (1)$$

Table 3 Simulation initial orientation, oscillation direction, oscillation amplitude, and oscillation forcing frequency.

Case no.	Initial angle of attack, deg	Initial sideslip angle, deg	Oscillation direction	Oscillation amplitude, deg	k, cycles/s
1	4	0	Pitch	5	1
2	10	0	Pitch	5	1
3	4	0	Roll	10	0.88
4	4	0	Yaw	5	0.44

V. Results

For each simulation, only the primary nondimensionalized aerodynamic coefficient used to compute the rate derivative is presented. The results are illustrated with STAR-CCM+ results in red, LAVA results in blue, and wind-tunnel data in black. The LAVA results are presented only for the pitch oscillation cases (Cases 1 and 2). The moments were computed with respect to the body axis, as illustrated in Fig. 1. The rolling moment coefficient C_l and yawing moment coefficients C_n were nondimensionalized using the wing reference area and wingspan, whereas the pitching moment coefficient C_m was nondimensionalized using the wing reference area and mean aerodynamic chord. The reference quantities are tabulated in Table 1.

The CFD-based hysteresis responses are compared against that of wind-tunnel data in terms of shape, enclosed area, and slope of the angle-of-attack extremities. The computed rate derivative values from CFD results are compared against that from the wind-tunnel data. It should be noted that wind-tunnel data were not corrected for the wind-tunnel wall interference effect.

A. Case 1: 4 Degrees Angle of Attack With ± 5 Degrees Oscillation Results

The C_m hysteresis responses due to oscillation in pitch axis, starting from 4 degrees angle of attack and oscillating ± 5 degrees, are plotted in Fig. 4. The CFD results underpredict the values of C_m compared to the wind-tunnel data. The wind-tunnel hysteresis response has the shape of an elongated ellipsoid, whereas the CFD results show a rounded ellipsoid. The CFD responses also show a thicker section at the middle of the ellipsoid compared to that of the wind-tunnel ellipsoid.

The slope of the CFD hysteresis responses between the angle-of-attack extremities, the area enclosed by the hysteresis response, and their relative errors to the wind-tunnel data are tabulated in Table 4. The relative errors were computed using the wind-tunnel data as the reference. Results show STAR-CCM+ data has a larger error on the slope relative to LAVA, 16.3 to 5.4 percent, respectively. For the enclosed area of the hysteresis response, STAR-CCM+ has a lower relative error of 9.8 percent, compared to LAVA of 20.6 percent.

The C_{mq} computed data using C_m hysteresis data are presented in Fig. 5 along with the relative error of the CFD- to wind-tunnel-based results. Fig. 5 shows C_{mq} from STAR-CCM+ has a smaller relative error of 23.1 percent compared to LAVA that has 37.7 percent error relative to the wind-tunnel data. Both CFD results, however, show more negative values of C_{mq} , which refers to higher pitch rate stability compared to the wind-tunnel data. Relating the hysteresis result to the accuracy of the C_{mq} , based on CFD, data shows that given a similar shape of the hysteresis response, accuracy of the enclosed area has both positive and the largest correlation to the accuracy of the C_{mq} value.

The discrepancy between the CFD- and wind-tunnel-data results may be due to the lack of tunnel wall and sting model in the simulation, which has been shown to influence both C_l and C_m [11]. Results published by Duensing [11] show that including the tunnel wall and sting apparatus increased both C_l and C_m for angle of attack ranges considered in this study for both LAVA and STAR-CCM+. This observation shows that wind-tunnel correction wall and sting correction to the experimental data, or the addition of a wind-tunnel wall and sting to the computational model, may decrease the discrepancy.

The discrepancies between the results of STAR-CCM+ and LAVA are due to numerous factors: differences in the method of discretization of the governing equation, differences in utilized numerical schemes, and differences in implementation, which may cause the observed discrepancies. In addition, LAVA that has finer mesh, may capture secondary flow physics that may not be captured by STAR-CCM+. Though the results presented show STAR-CCM+ having more accurate results compared to the wind-tunnel data, these results should be considered, noting that the wind-tunnel data were not corrected for the wind-tunnel wall and sting effect, and the CFD simulations assumed freestream farfield.

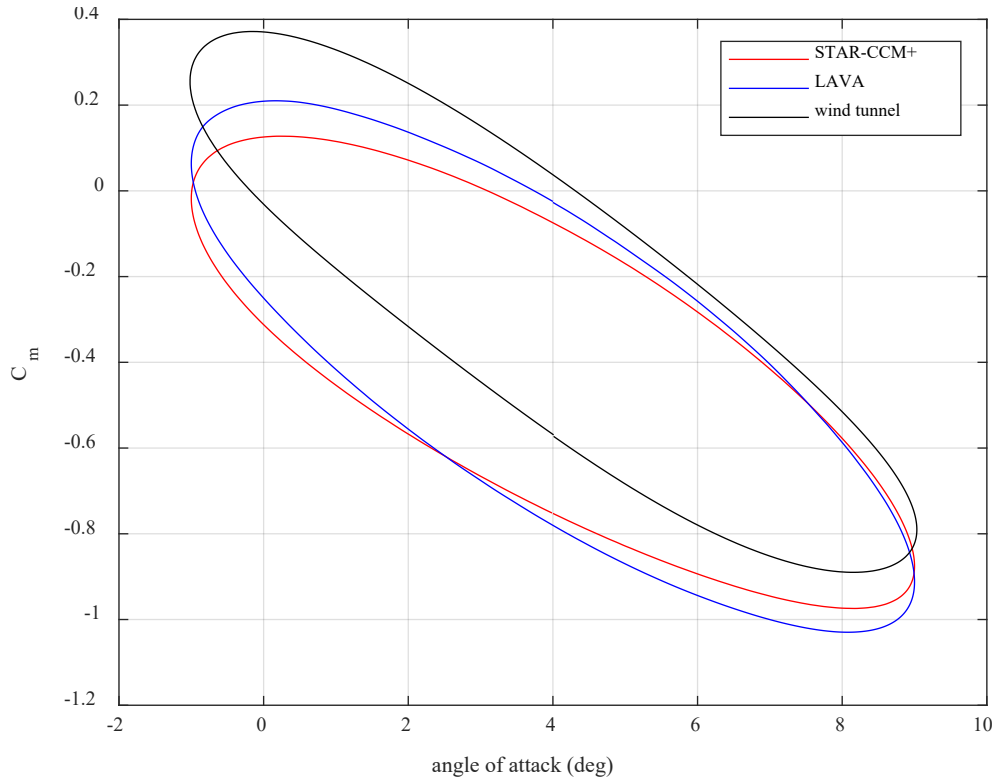


Fig. 4 Angle of attack 4 degrees, ± 5 degrees pitch angle oscillation: C_m versus angle of attack for wind-tunnel (black); STAR-CCM+ (red); and LAVA data (blue).

Table 4 Angle of attack 4 degrees, ± 5 degrees C_m , hysteresis slope, enclosed area, and relative errors for wind-tunnel, STAR-CCM+, and LAVA data.

C_m	Slope, per deg	Area enclosed, deg	Slope rel err, %	Area rel err, %
STAR-CCM+	-4.9300	5.3800	-16.3	9.8
LAVA	-5.5700	5.9100	-5.4	20.6
Wind tunnel	-5.8900	4.9000	--	--

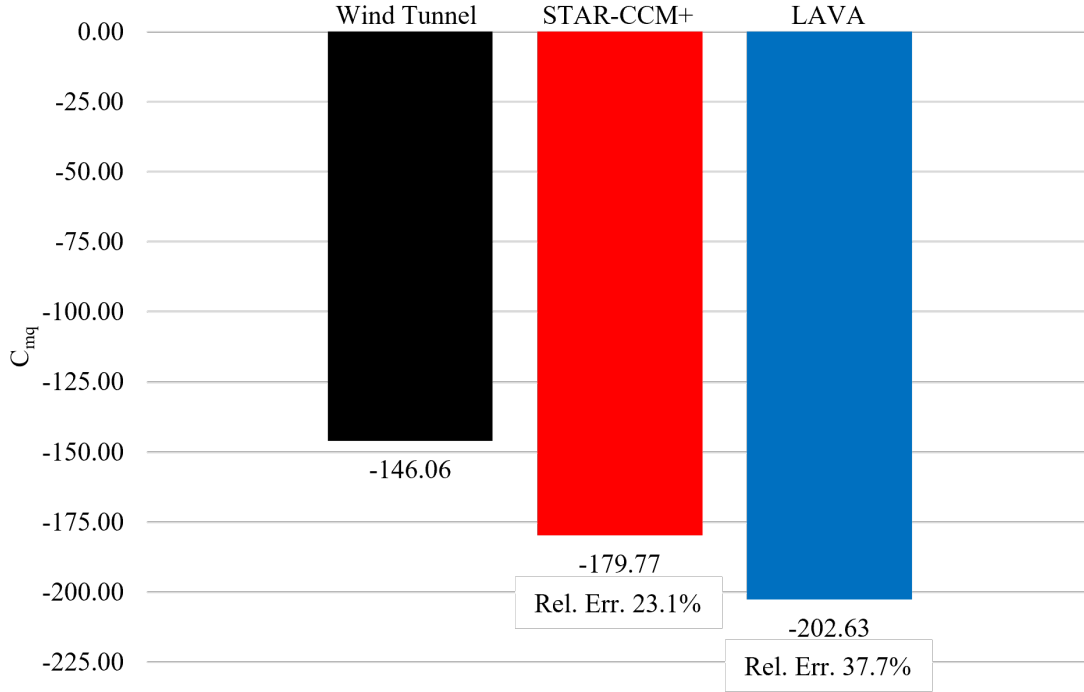


Fig. 5 Angle of attack 4 degrees, ± 5 degrees pitch angle oscillation: C_{mq} and relative error percentage for wind-tunnel (black); STAR-CCM+ (red); and LAVA data (blue).

B. Case 2: 10 Degrees Angle of Attack With ± 5 Degrees Oscillation Results

The C_m results of wind-tunnel tests, STAR-CCM+, and LAVA are presented in this section for pitch oscillation starting at 10 degrees angle of attack with oscillation amplitude of ± 5 degrees. The C_m hysteresis results are presented in Fig. 6. Both STAR-CCM+ and LAVA results show elliptically shaped hysteresis response, whereas the wind-tunnel data show a skewed ellipsoid. Results also show that CFD predicts more negative C_m compared to wind-tunnel data for the range of angle of attack evaluated.

The slope of the CFD hysteresis response between the angle-of-attack extremities, the area enclosed by the hysteresis response, and their relative errors to the wind-tunnel data are tabulated in Table 5. The relative errors were computed using the wind-tunnel data as the reference. Results show STAR-CCM+ has a smaller error on the slope relative to LAVA at 10.9 and 18.0 percent, respectively. Similarly, for the enclosed area of the hysteresis response, STAR-CCM+ has a lower relative error of 25.5 percent compared to LAVA at 48.1 percent. The errors of the slope and enclosed area for both STAR-CCM+ and LAVA for Case 2 are larger than that of Case 1 due to simulation being at a higher angle of attack, resulting in more complex flow phenomena that may not be captured in the simulations. Higher angle of attack also increases the influence of the tunnel wall and sting which were not modeled in the simulations [11], thus increasing error between the CFD results and the wind-tunnel experiments.

The computed C_{mq} and the relative error of CFD results with respect to wind tunnel are presented in Fig. 7. Similar to the lower initial angle of attack case (Case 1), C_{mq} results based on CFD show more negative value compared to those that were based on wind-tunnel data, indicating higher pitch damping and longitudinal stability. The relative errors of CFD are higher compared to Case 1 with STAR-CCM+ showing an error at 45.5 percent and LAVA at 73.3 percent. This result also correlates to errors within enclosed area; more accurate prediction of enclosed areas results in a more accurate prediction of C_{mq} value. The error of C_{mq} may be higher than Case 1 because Case 2 oscillates about 10 degrees angle of attack, which may present more complex flow physics compared to oscillation centered at 4 degrees angle of attack.

The discrepancies between the results of STAR-CCM+ and LAVA are due to similar factors that were described previously in Section V, A. For this case, impacts may be even more pronounced due to a higher angle of attack.

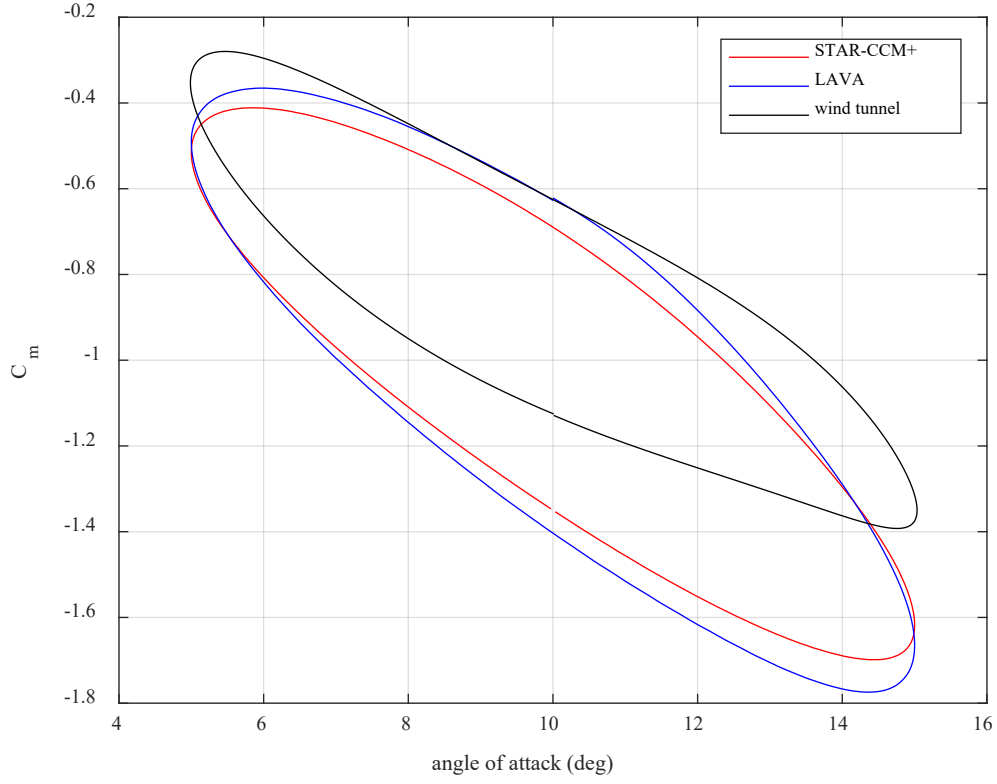


Fig. 6 Angle of attack 10 degrees, ± 5 degrees pitch angle oscillation: C_m versus angle of attack for wind-tunnel (black); STAR-CCM+ (red); and LAVA data (blue).

Table 5 Angle of attack 10 degrees, ± 5 degrees pitch angle oscillation: C_m , hysteresis slope, enclosed area, and relative errors for wind-tunnel, STAR-CCM+, and LAVA data.

C_m	Slope, per deg	Area enclosed, deg	Slope rel err, %	Area rel err, %
STAR-CCM+	-6.2918	5.1700	10.9	25.5
LAVA	-6.6924	6.1000	18.0	48.1
Wind Tunnel	-5.6712	4.1200	--	--

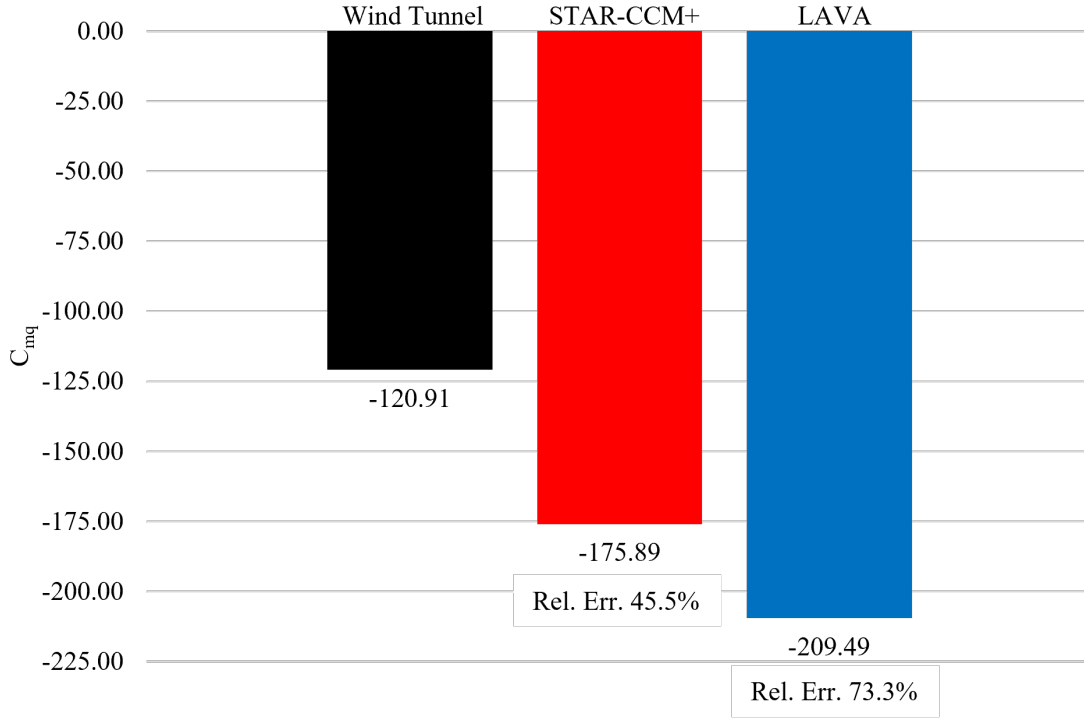


Fig. 7 Angle of attack 10 degrees, ± 5 degrees pitch angle oscillation: C_{mq} and relative error percentage for wind-tunnel (black); STAR-CCM+ (red); and LAVA data (blue).

C. Case 3: 4 Degrees Angle of Attack With 0 ± 10 Degrees Roll Angle Oscillation Results

The C_l and C_n hysteresis response from STAR-CCM+ and wind-tunnel experiments of 10 degrees amplitude roll angle oscillation are presented in Fig. 8. The aircraft model is fixed at 4 degrees angle of attack and oscillates strictly about the x axis in the body axis system, as shown in Fig. 1. This prevents the aircraft from experiencing flow from the sideslip angle that would have been induced by the roll. Examining the C_l hysteresis, CFD results compare well with the wind-tunnel data. The shape of the C_l hysteresis of both STAR-CCM+ and wind-tunnel data resemble a circle. The slope of the hysteresis between the roll angle extremities and the area enclosed by the hysteresis response is tabulated in Table 6 for C_l and Table 7 for C_n . As the hysteresis responses appear circular, the slope is approximately to zero for both STAR-CCM+ and wind-tunnel data, resulting in a 0.01 per degree. The area enclosed between the two responses is similar with STAR-CCM+, having an area that is larger than that of the wind tunnel by 4.5 percent.

The hysteresis of C_n shows a circular shape similar to C_l results; however, STAR-CCM+ results show very symmetric results with respect to the $C_n=0$ line, whereas the wind-tunnel data is biased toward the negative C_n . The slope between the roll angle extremities is approximately zero for both results. The area enclosed by the hysteresis response, STAR-CCM+, is 21.7 percent smaller than the wind-tunnel data; however, the magnitude of the area itself is an order of magnitude smaller compared to area of the response of C_l .

The computed C_{lp} and C_{np} are plotted in Fig. 9 along with the relative error of STAR-CCM+ with respect to results computed using the wind-tunnel data. The C_{lp} results from STAR-CCM+ compare well with those of wind-tunnel data, with a relative error of 5.6 percent, indicating that the STAR-CCM+ result has a higher roll damping, indicating larger lateral stability compared to the wind-tunnel data. The C_{np} has a larger error compared to C_{lp} , with 20.0 percent error; however, the magnitude of C_{np} is small because C_n is a secondary effect of the roll maneuver. Similar to pitch cases, results of the rate derivative correlate positively with the accuracy of the enclosed area.

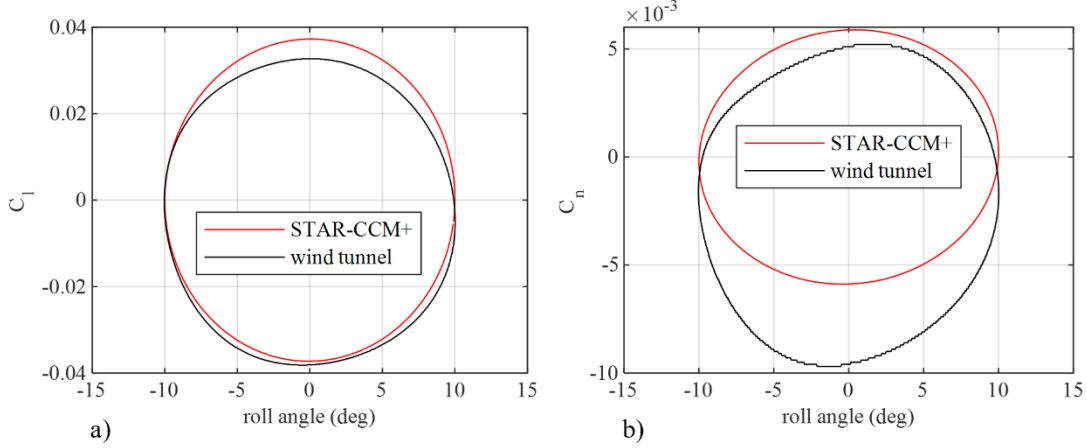


Fig. 8 Angle of attack 4 degrees, 0 ± 10 degrees roll angle oscillation: hysteresis response from STAR-CCM+ (red) and wind-tunnel data (black): a) C_l , and b) C_n .

Table 6 Angle of attack 4 degrees, 0 ± 10 degrees roll angle oscillation: C_l , hysteresis slope, enclosed area, and relative errors for wind-tunnel and STAR-CCM+ data.

C_l	Slope, per deg	Area enclosed, deg	Slope abs err, per deg	Area rel err, %
STAR-CCM+	0.0002	1.1700	0.01	4.5
Wind Tunnel	-0.0129	1.1200	--	--

Table 7 Angle of attack 4 degrees, 0 ± 10 degrees roll angle oscillation: C_n , hysteresis slope, enclosed area, and relative errors for wind-tunnel and STAR-CCM+ data.

C_n	Slope, per deg	Area enclosed, deg	Slope abs err, per deg	Area rel err, %
STAR-CCM+	0.0014	0.1800	0.00	-21.7
Wind Tunnel	-0.0003	0.2300	--	--

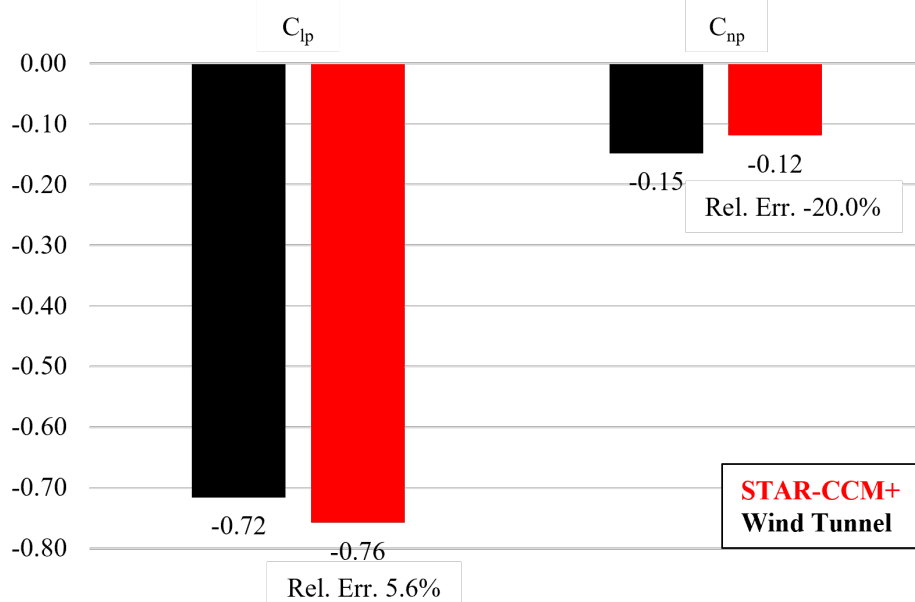


Fig. 9 Angle of attack 4 degrees, 0 ± 10 degrees roll angle oscillation: C_{lp} , C_{np} , and relative error percentage for STAR-CCM+ (red) and wind-tunnel data (black).

D. Case 4: 4 Degrees Angle of Attack With 0 ± 5 Degrees Yaw Angle Oscillation Results

The hysteresis of C_l and C_n from STAR-CCM+ and wind-tunnel data due to yaw oscillation are presented in Fig. 10. Both C_l and C_n hysteresis has an elongated ellipsoid shape at an angle. The STAR-CCM+ overpredicts values of C_l compared to wind-tunnel values while underpredicting values of C_n . The slope of the hysteresis between the roll angle extremities and the area enclosed by the hysteresis response are tabulated in Table 8 for C_n and Table 9 for C_l . The error of the slope between the yaw angle extremities for C_l and C_n is -26.1 and 2.6 percent, respectively; however, the slope is in the order of 10^{-1} so that values of the absolute error are small.

The errors of the area enclosed by the hysteresis responses of C_l and C_n are 20.6 and 15.9 percent, respectively, for STAR-CCM+ with respect to wind tunnel; however, similar to the slope, the values of the area are small, on the order of 10^{-2} , which are reflected on the error of C_{lr} and C_{nr} , shown in Fig. 11. Results show C_{lr} and C_{nr} computed from STAR-CCM+ have a 1.7 and 0.8 percent error, respectively, with respect to wind-tunnel data. Similar to pitch cases, results of the rate derivative correlate positively with accuracy of the enclosed area.

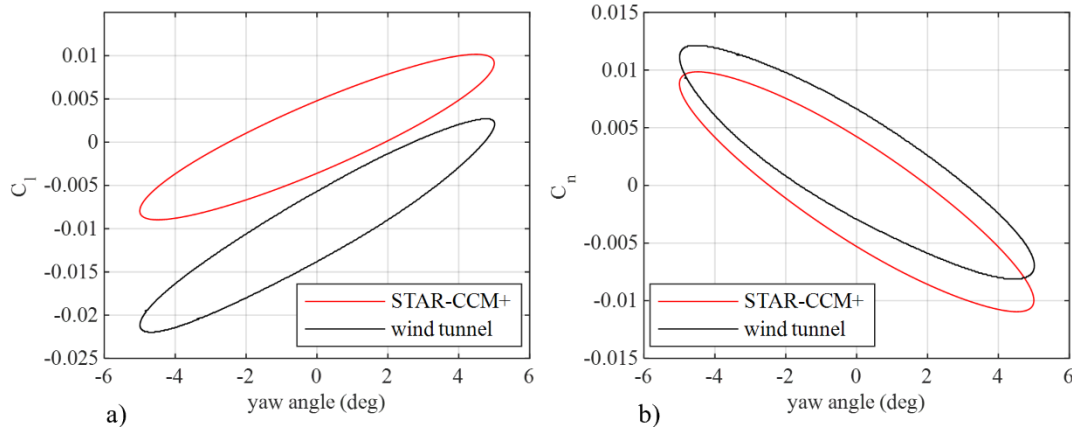


Fig. 10 Angle of attack 4 degrees, 0 ± 5 degrees yaw angle oscillation: hysteresis response from STAR-CCM+ (red) and wind-tunnel data (black): a) C_l ; and b) C_n .

Table 8 Angle of attack 4 degrees, 0 ± 5 degrees yaw angle oscillation: C_n hysteresis slope, enclosed area, and relative errors for wind-tunnel and STAR-CCM+ data.

C_n	Slope, per deg	Area enclosed, deg	Slope rel err, %	Area rel err, %
STAR-CCM+	-0.1074	0.0867	2.6	15.9
Wind Tunnel	-0.1047	0.0748	N/A	N/A

Table 9 Angle of attack 4 degrees, 0 ± 5 degrees yaw angle oscillation: C_l hysteresis slope, enclosed area, and relative errors for wind-tunnel and STAR-CCM+ data.

C_l	Slope, per deg	Area enclosed, deg	Slope rel err, %	Area rel err, %
STAR-CCM+	0.0977	0.0778	-26.1	20.6
Wind Tunnel	0.1323	0.0646	N/A	N/A

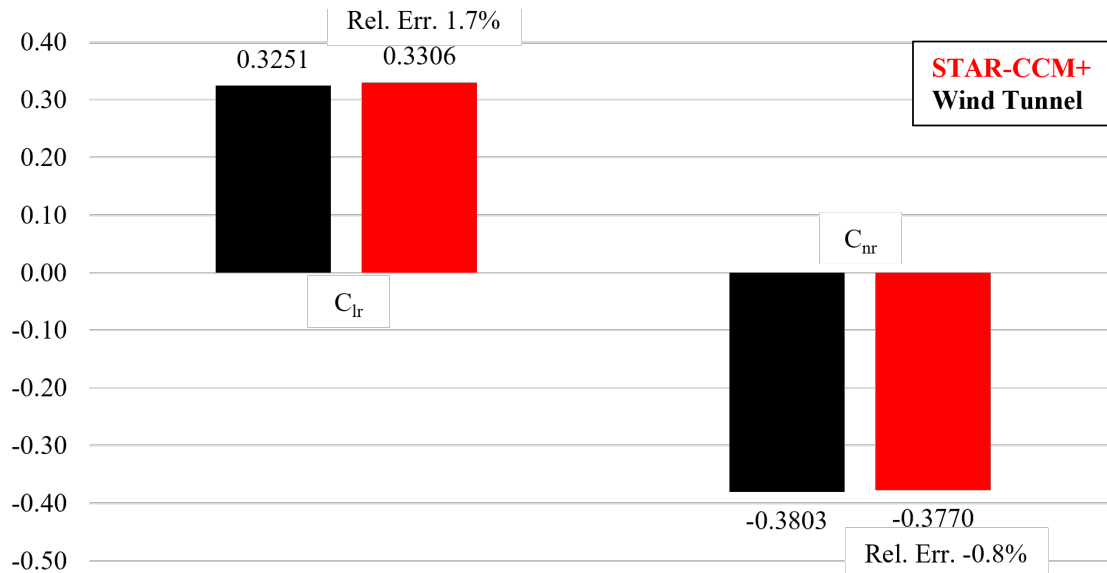


Fig. 11 Angle of attack 4 degrees, 0 ± 5 degrees yaw angle oscillation: C_{lr} , C_{nr} , and relative error percentage for STAR-CCM+ (red) and wind-tunnel data (black).

VI. Conclusion

This paper presented the analysis of rate derivatives of X-57 wind-tunnel model data computed using CFD simulations and results were compared to the rate derivatives computed using the wind-tunnel experimental data. Large discrepancies were shown in C_{mq} , up to 73 percent, and between the CFD results and wind-tunnel data due to complex flow physics induced by the high angle of attack and lack of a wind-tunnel wall and sting model in the CFD simulations. Lateral and directional rate derivatives, except for C_{np} , compared well between the CFD and the wind-tunnel results: C_{lp} with an error of 5.6 percent, C_{lr} with an error of 1.7 percent, and C_{nr} with an error of 0.8 percent. A larger relative error of 20 percent was shown for C_{np} ; however, the magnitude of C_{np} was small compared to other variables.

Several geometric traits of the hysteresis, such as shape, enclosed area, and slope of the angle-of-attack extremities were evaluated for their influence on the accuracy of the computed rate derivatives. Results showed that, given a similarly shaped hysteresis response, a discrepancy between the computed rate derivative of CFD and wind-tunnel data decreased with a decrease in error of the area enclosed by the hysteresis response, despite the hysteresis of CFD errors in the magnitude of the coefficient used to compute the rate derivatives.

References

- [1] AIAA Stability and Control Prediction Workshop (S&CPW), Sponsored by the Applied Aerodynamics and Atmospheric Flight Mechanics Technical Committees, Page Last Updated: May 22, 2024, <https://sandcpw.wordpress.com/> [retrieved 13 June 2024].
- [2] Yoo, S. Y., and Duensing, J. C., "Computational Analysis of the External Aerodynamics of the Unpowered X-57 Mod-III Aircraft," AIAA Paper 2019-3698, June 2019. doi: 10.2514/6.2019-3698
- [3] Siemens, "Simcenter Star-CCM+ CFD Software," 2019. <https://mdx.plm.automation.siemens.com/star-ccm-plus>
- [4] Kiris, C. C., Housman, J. A., Barad, M. F., Brehm, C., Sozer, E., and Moini-Yeta, S., "Computational framework for Launch, Ascent, and Vehicle Aerodynamics (LAVA)," Aerospace Science and Technology, Vol. 55, August 2016, pp. 189-219. doi: 10.1016/j.ast.2016.05.008
- [5] Spalart, P., and Allmaras, S., "A One-Equation Turbulence Model for Aerodynamic Flows," AIAA Paper 1992-0439, January 1992. doi: 10.2514/6.1992-439
- [6] Shur, M. L., Strelets, M. K., Travin, A. K., and Spalart, P. R., "Turbulence modeling in rotating and curved channels: assessing the Spalart-Shur Correction," AIAA Journal, 2000, 38(5), pp. 784-792.

- [7] Yamamoto, K., Tanaka, K., and Murayama, M., “Effect of a Nonlinear Constitutive Relation for Turbulence Modeling on Predicting Flow Separation at Wing-Body Junction of Transonic Commercial Aircraft,” AIAA Paper 2012-2895, June 2012. doi: doi.org/10.2514/6.2012-2895
- [8] Weiss, J. M., Maruszewski, J. P., and Smith, W. A., “Implicit Solution of Preconditioned Navier-Stokes Equations Using Algebraic Multigrid,” AIAA Journal, Vol. 37, No. 1, 1999, pp. 29-36. doi: 10.2514/2.689
- [9] Weiss, J. M., and Smith, W. A., “Preconditioning applied to variable and constant density flows,” AIAA Journal, Vol. 33, No. 11, 1995, pp. 2050-2057. doi: 10.2514/3.12946
- [10] Venkatakrishnan, V., “On the Accuracy of Limiters and Convergence to Steady State Solutions,” AIAA Paper 93-0880, January 1993. doi: 10.2514/6.1993-880
- [11] Turkel, E., “Preconditioned methods for solving the incompressible and low speed compressible equations,” Journal of computational physics, Vol. 72, No. 2, 1987, pp. 277–298.
- [12] Duensing, J. C., Yoo, S. Y., Maldonado, D., Housman, J. A., Jensen, J. C., and Kiris, C. C., “Establishing Best Practices for X57 Maxwell CFD Database Generation,” AIAA Paper 2019-0274, January 2019. doi: 0.2514/6.2019-0274
- [13] Housman, J. A., Kiris C. C., and Hafez, M. M., “Time-Derivative Preconditioning Methods for Multicomponent Flows - Part I: Riemann Problems,” Journal of Applied Mechanics, Vol. 76, No. 2, March 2009. doi: 10.1115/1.3072905
- [14] Housman, J., Kiris C. C., and Hafez, M. M., “Time-Derivative Preconditioning Methods for Multicomponent Flows - Part II: Two-Dimensional Applications,” Journal of Applied Mechanics, Vol. 76, No. 3: 031013 (12 pages), March 2009. doi: 10.1115/1.3086592
- [15] Anonymous, “3rd AIAA CFD High Lift Prediction Workshop Gridding Guidelines,” Sponsored by the AIAA Applied Aerodynamics Technical Committee, June 2016. <https://hiliftpw.larc.nasa.gov/Workshop3/GriddingGuidelines-HiLiftPW3-v10.pdf> [retrieved 13 June 2024].
- [16] Cadence, “Fidelity Pointwise for CFD Meshing,” San Jose, California, 2024. https://www.cadence.com/en_US/home/tools/system-analysis/computational-fluid-dynamics/pointwise.html [retrieved 13 June 2024].
- [17] Chan, W. M., Pandya, S. A., Rogers, S. E., Jensen, J. C., Lee, H. C., Kao, D. L., Buning, P. G., Meakin, R. L., Boger, D. A., and Nash, S. M., “Chimera Grid Tools User’s Manual,” Version 2.2, June 2018. <https://www.nas.nasa.gov/publications/software/docs/chimera/pages/man.html> [retrieved 13 June 2024].