



Icing Simulation Research Supporting the Ice-Accretion Testing of Large-Scale Swept-Wing Models

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Contents

1.0	Background and Previous Work	1
1.1	Introduction.....	1
1.2	Scope and Objectives.....	4
1.3	Approach.....	4
2.0	CFD Analysis of CRM65 Wing-Body Configuration.....	5
2.1	Geometry and Grid Setup	5
2.2	Numerical Scheme	5
2.3	Results.....	7
2.4	Attachment Line Extraction.....	7
3.0	CFD Analysis of IRT Test Articles.....	10
3.1	Setup	10
3.2	Results.....	10
4.0	Ice Accretion Analysis for the CRM65 WB and IRT Test Articles.....	12
4.1	LEWICE3D Setup	12
4.2	Results for CRM65 Wing-Body Configuration	13
4.3	Results for IRT Test Articles	16
4.4	Ice Shape Comparison Exercise.....	30
5.0	Full-Scale Midspan Model Design for the IRT.....	30
5.1	Geometry Design Process.....	30
5.2	CFD Analysis of Full Scale Midspan Model.....	32
5.3	Flap Design for Full-Scale Model.....	40
5.4	Model Installation and CFD Analysis of the Simple-Hinge Flap Model.....	42
5.5	Aerodynamic Calibration of the Full-Scale Simple-Hinge Model.....	50
5.6	Updated Full-Scale Simple-Hinge Model.....	50
6.0	Ice Accretion Analysis of Full-Scale Midspan Model.....	53
6.1	LEWICE3D Setup	53
6.2	Results.....	53
7.0	Summary	60
8.0	Supporting Data	60
	References.....	61

List of Figures

Figure 1.2.—	Schematic comparison of a hybrid and a full-scale section of the CRM65.....	2
Figure 1.3.—	Schematic drawing of a model in the IRT test section.....	2
Figure 1.4.—	Comparison of CFD computed pressure coefficients with IRT data for the inboard model.....	3
Figure 1.5.—	Comparison of CFD computed pressure coefficients with IRT data for the midspan model.....	3
Figure 1.6.—	Comparison of CFD computed pressure coefficients with IRT data for the outboard model.....	4
Figure 2.1.—	CRM65 wing-body model.....	5
Figure 2.2.—	Convergence characteristics for a sample run. (a) Residuals convergence. (b) Forces and moment convergence.....	6
Figure 2.3.—	Identification of Attachment line location by $C_f = 0$ line (in yellow) and streamlines (in black).....	8
Figure 2.4.—	Identification of Attachment line location by $C_f = 0$ line and $C_{p \max}$	8
Figure 2.5.—	Attachment line location across span for CRM65 WB configuration.....	9
Figure 3.1.—	Grid system setup for simulation in the IRT.....	11

Figure 4.1.—Drop size distributions considered for LEWICE3D analysis.	12
Figure 4.2.—IRT 2015 drop distribution separation into 7 bins, used in LEWICE3D analysis.	13
Figure 4.3.—WB33 LEWICE3D ice shapes.	14
Figure 4.4.—WB41 LEWICE3D ice shapes.	15
Figure 4.5.—WB52 LEWICE3D ice shapes. (a) Overall view of ice shapes. (b) Close-up view of ice shapes.	15
Figure 4.6.—Temperature sweep, warmer -3.7°C	17
Figure 4.7.—Temperature sweep, mid -17.4°C	17
Figure 4.8.—Temperature sweep, colder -26.2°C	18
Figure 4.9.—Ice shape comparison for temperature sweep conditions.	18
Figure 4.10.—Higher AoA, colder -8.6°C	19
Figure 4.11.—Higher AoA, warmer -3.7°C	19
Figure 4.12.—Ice shape comparison for higher AoA conditions.	20
Figure 4.13.—Lower AoA, warmer -6.1°C	21
Figure 4.14.—Lower AoA, colder -8.6°C	21
Figure 4.15.—Ice shape comparison for lower AoA conditions.	22
Figure 4.16.—Higher speed, colder -18.0°C	23
Figure 4.17.—Higher speed, warmer -6.3°C	23
Figure 4.18.—Ice shape comparison for higher speed conditions.	24
Figure 4.19.—Beak ice shapes.	25
Figure 4.20.—Beak ice temperature sweep.	25
Figure 4.21.—WB52 T-13, reference.	26
Figure 4.22.—WB52 T-13, scale.	26
Figure 4.23.—Comparison of ice shapes for WB52 T-13 conditions.	27
Figure 4.24.—IRT repeat runs of the cold temperature sweep at -26.2°C	28
Figure 4.26.—Ice shapes sensitivity to drop distribution for midspan model run TH2436.	29
Figure 4.27.—Ice shapes sensitivity to drop distribution for inboard model run TG2416.	29
Figure 5.1.—Process of generating the full-chord test article.	31
Figure 5.2.—Force convergence histories for full-scale model.	32
Figure 5.3.—Time-accurate calculations at high angle of attack.	33
Figure 5.4.—Effect of time-accuracy on full-scale midspan model. (a) Snapshot of the flow field at the end of the nontime accurate solution. (b) Snapshot of the flow field after 0.44 sec.	34
Figure 5.5.—Forces and moments on the full-scale model. (a) Turntable maximum load = 13,750 lbf. (b) Turntable maximum moment = $\pm 10,000$ ft-lbf.	35
Figure 5.6.—Stagnation line distance from highlight for full-scale model.	36
Figure 5.7.—Stagnation line location as function of angle of attack.	37
Figure 5.8.—Aerodynamic calibration of stagnation line location.	38
Figure 5.8.—Concluded.	39
Figure 5.9.—Simple-hinge flap models.	40
Figure 5.10.—Effect of flap size and deflection on model lift.	41
Figure 5.11.—Flap effectiveness.	42
Figure 5.12.—Effects of model location on flow field.	43
Figure 5.13.—Effects of model location on turntable loads and moments.	44
Figure 5.14.—Effects of model position on maximum pressure location.	45
Figure 5.15.—Effects of model position on streamwise wrap distance from highlight.	46
Figure 5.16.—Relations between model location and loads reduction.	46
Figure 5.17.—Effect of model upstream location on pitching moment.	47
Figure 5.18.—Lift on full-scale, simple-hinge flap model ($\Delta X = -40$ in., $M_{\infty} = 0.32$).	48
Figure 5.19.—Pitching moment on full-scale, simple-hinge flap model ($\Delta X = -40$ in., $M_{\infty} = 0.32$).	49

Figure 5.20.—Wrap distance to stagnation line on full-scale, simple-hinge flap model ($\Delta X = -40$ in., $M_\infty = 0.32$).....	49
Figure 5.21.—Aerodynamic calibration of full-scale simple-hinge flap model.	50
Figure 5.22.—Original leading edge geometry discrepancies on cuts normal to the leading edge. (a) Overall view of all shapes. (b) Close-up view of hybrid to full-scale comparison showing significant mismatch. (c) Close-up view of IFB to full-scale comparison.....	51
Figure 5.23.—Leading edge geometries remedied (normal cuts to leading edge). (a) Overall view of all shapes. (b) Close-up view of hybrid to full-scale comparison showing match.	52
Figure 6.1.—Pressure distribution comparison between hybrid and full-scale models. (a) Overall view. (b) Close-up view of leading edge region. Note: $s = 0$ is defined at the highlight (clean airfoil point of minimum X).....	54
Figure 6.2.—Collection efficiency comparison of hybrid model, full-chord model, and IFB, with IRT MVD = $25\ \mu\text{m}$. Note: $s = 0$ is defined at the highlight (clean airfoil point of minimum X).	55
Figure 6.3.—Collection efficiency comparison of hybrid model, full-chord model, and IFB, with IRT MVD = $27.6\ \mu\text{m}$. Note: $s = 0$ is defined at the highlight (clean airfoil point of minimum X). ...	56
Figure 6.4.—Venetian blind scallop full chord model to IFB comparison.....	57
Figure 6.5.—Max scallop full chord model to IFB comparison.....	57
Figure 6.6.—Small gap scallop full chord model to IFB comparison.	58
Figure 6.7.—Incomplete scallop full chord model to IFB comparison.	58
Figure 6.8.—Streamwise/rime full chord model to IFB comparison.....	59
Figure 6.9.—WB33 direct App. C full chord model to IFB comparison.....	59

List of Tables

Table 2.1.—Summary of Flight Conditions.....	7
Table 2.2.—Summary of Forces and Moment Coefficients for CRM WB Configuration.....	7
Table 2.3.—Attachment Line Locations for CRM WB Configuration.....	9
Table 3.1.—CFD Run Matrix for IRT Test Articles.....	11
Table 4.1.—IRT 2015 7-Bin Drop Distributions.....	13
Table 4.2.—Icing Conditions for CRM65 WB Configuration	14
Table 4.3.—Icing Conditions for CRM65 WB Configuration	16
Table 5.1.—Stagnation Line Wrap Distance as Function of Flap Deflection.....	51
Table 5.2.—Interpolated Flap Deflection for Nominal Reference Cases	51
Table 5.3.—Stagnation Line Wrap Distance as Function of Flap Deflection.....	52
Table 5.4.—Interpolated Flap Deflection for Nominal Reference Cases for Updated Model.....	52
Table 6.1.—Icing Conditions for Full-Scale Midspan Model in the IRT Test Section	53
Table 6.2.—Impingement Comparison of the Hybrid Model, Full-Chord Model, and IFB.....	56

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1.0 Background and Previous Work

1.1 Introduction

Boeing has designed and analyzed three test articles for the Icing Research Tunnel in support of ice-accretion testing of large-scale swept-wing models, followed by a design and analysis of a Full-Scale model with a simple hinged flap. Ice shapes were created for these models and compared with ice shapes of a Wing-Body configuration.

The work summarized in this report is a continuation of NASA's *Large-Scale, Swept-Wing Test Articles Fabrication; Research and Test Support for NASA IRT* contract (NNC10BA05-NNC14TA36T) performed by Boeing under the NASA Research and Technology for Aerospace Propulsion Systems (RTAPS) contract. In the study conducted under RTAPS, a series of icing tests in the Icing Research Tunnel (IRT) have been conducted to characterize ice formations on large-scale swept wings representative of modern commercial transport airplanes. The outcome of that campaign was a large database of ice-accretion geometries that can be used for subsequent aerodynamic evaluation in other experimental facilities and for validation of ice-accretion prediction codes.

The baseline swept wing geometry for this project was the Common Research Model (CRM) (Refs. 1 to 3). The research team decided to use a 65 percent version of the CRM (CRM65) as the full-scale baseline for this study, which is representative of existing narrow-body commercial transport such as the B757-200 or B737-900. It was also determined that the full configuration of the model is not critical for the study objectives and a configuration comprised of the wing and body only was chosen (WB). The geometric characteristics of the wing are shown in Figure 1.1. Also shown are the three span stations chosen as the basis for the test articles.

It is worth noting that the CRM geometry used in this task is based on the high-speed configuration and lacks geometrical features essential to low-speed flight such as a nacelle, chine and partial-span ice resulting from a wing ice protection system.

Because the size of the test section in the IRT (6 by 9 ft) is not large enough to accommodate a full scale CRM65 test article, the research team resorted to the design of a "hybrid" test model (Ref. 4). The hybrid model maintains the full scale leading edge geometry in the nose region of interest for ice formation. The aftbody of the wing section is truncated in a way that maintains the general characteristics of the flow field of the full scale wing. In addition, a separate flap element is installed in order to ensure the appropriate flow field, including the location of the stagnation line, needed for the generation of the appropriate ice accretion. A comparison between the full-scale section, normal to the leading edge, and the hybrid section and its flap is shown in Figure 1.2, while an example of a test article in the IRT test section is shown in Figure 1.3. Each model had three streamwise rows of pressure taps located at 18, 36, and 54 in., above the test-section floor. The ice-accretion data were acquired with a 3-D scanning system.

65% Scale CRM Characteristics

- Semispan = 62.7 ft
- Root chord (symmetry plane) = 29.0 ft
- Root chord (fuselage side of body) = 25.4 ft
- Tip chord = 5.8 ft
- Mean aerodynamic chord = 15.0 ft
- Semispan area = 873 ft²
- Aspect Ratio = 9.0
- Taper Ratio = 0.28
- Sweep angle ($c/4$) = 35 deg.

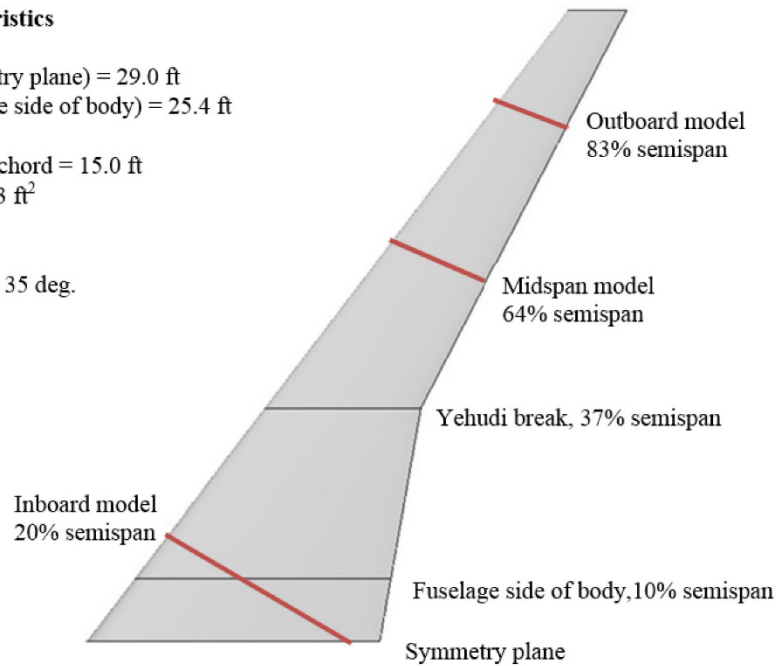


Figure 1.1.—Summary of 65 percent scale CRM geometric characteristics, adapted from Vassberg et al. (Ref. 1). Also indicated are the semispan locations of the three NASA IRT models.

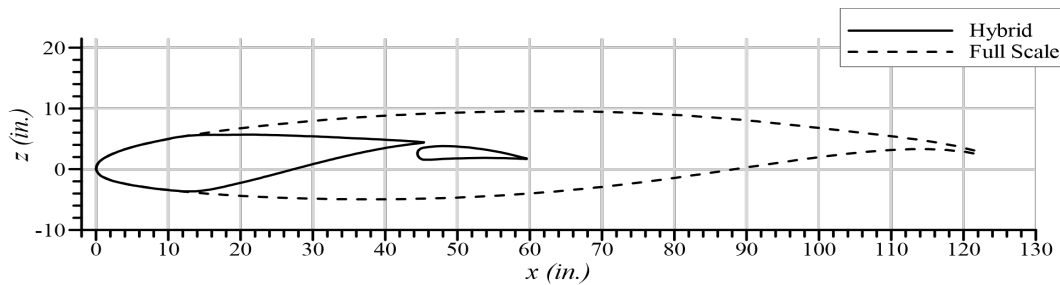


Figure 1.2.—Schematic comparison of a hybrid and a full-scale section of the CRM65.

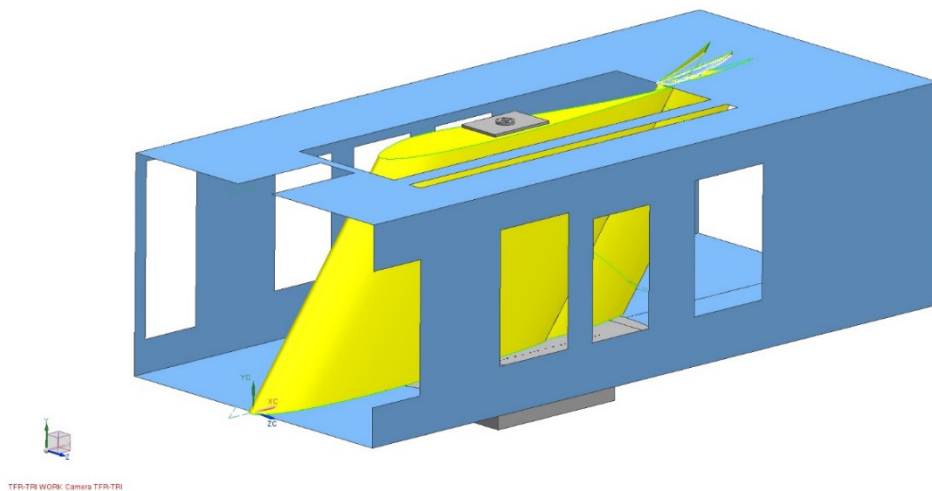


Figure 1.3.—Schematic drawing of a model in the IRT test section.

As part of the RTAPS contract (NNC10BA05-NNC14TA36T) Boeing performed a series of Computational Fluid Dynamics (CFD) simulations in support of the test article design (Refs. 5 and 6). At the completion of the test campaign a new set of simulations were obtained using the actual test conditions as input. The CFD results were compared with the aerodynamic data collected at the test. A comparison of surface pressure coefficients (C_p) between the Boeing CFD results, using the OVERFLOW code and test measurements are presented in Figure 1.4, Figure 1.5, and Figure 1.6 for the Inboard Model, the Midspan Model and the Outboard Model, respectively. Each figure includes two plots. On the left, a plot of C_p distribution in the chordwise direction (x) at three spanwise cuts along the model and on the right, the C_p distribution at the center of the model (36 in. from the floor) near the location of maximum C_p . Note that in this plot C_p is plotted as a function of the wrap distance taken in the streamwise direction from the wing highlight where positive values are on the lower surface.

As a whole, there is good agreement between the IRT data and Boeing's CFD C_p distribution. The location of the maximum C_p , used as an indicator for the stagnation point location, matches well for the Midspan and Outboard Models. The discrepancy in maximum C_p location for the Inboard Model can be attributed to the small number of pressure taps at the area of interest which can lead to error in the exact location of $C_{p_{max}}$.

The CFD-generated flow fields were used by Boeing to generate ice shapes using LEWICE3D. The version of the code used has been modified by Boeing to include required improvements ("bug fixes"), which mostly affect higher speed cases and cases with larger leading edge radii. NASA and Boeing are

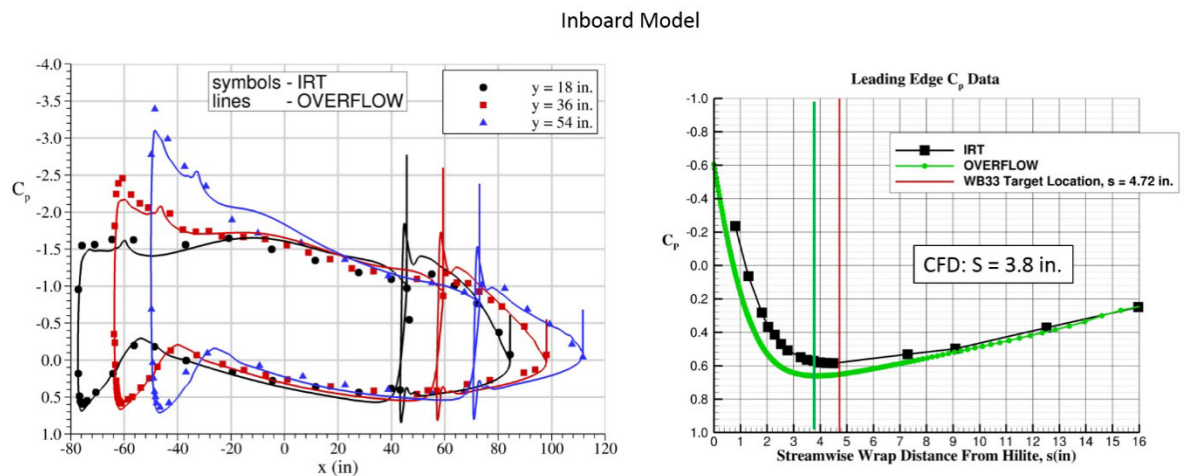


Figure 1.4.—Comparison of CFD computed pressure coefficients with IRT data for the inboard model.

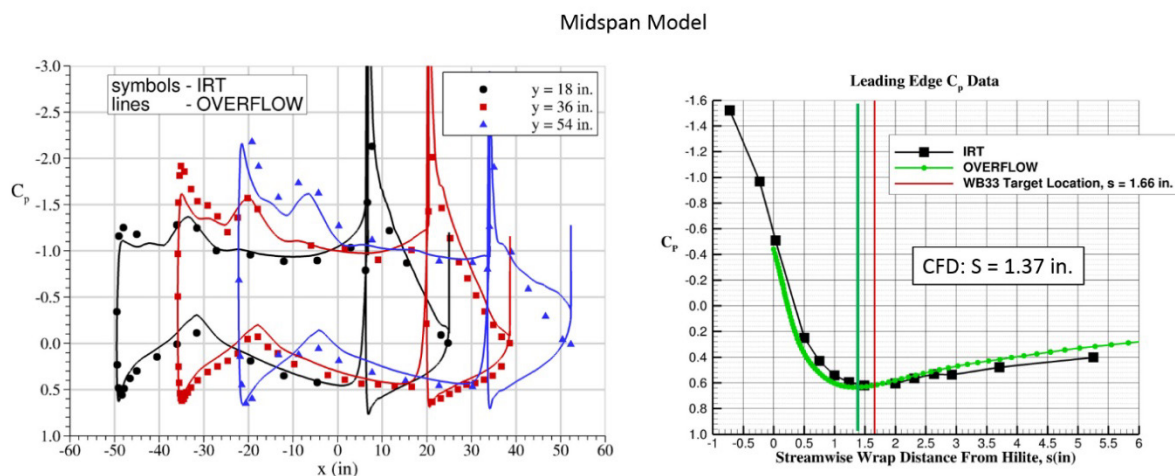


Figure 1.5.—Comparison of CFD computed pressure coefficients with IRT data for the midspan model.

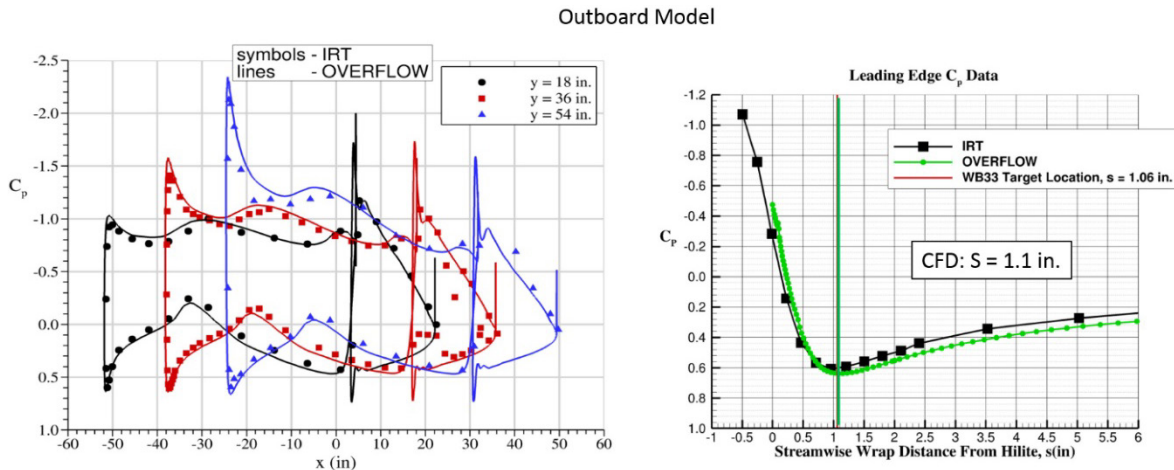


Figure 1.6.—Comparison of CFD computed pressure coefficients with IRT data for the outboard model.

collaborating to understand the impact of these changes relative to potential updates of LEWICE3D. The selected icing conditions to be analysed by LEWICE3D were based initially upon the Code of Federal Regulations Part 25 Appendix C continuous maximum envelope (App. C) and which define the droplet Mean Volumetric Diameter (MVD), cloud Liquid Water Content (LWC) and temperature. The ice shapes produced using the Boeing version of LEWICE3D show a good agreement with the ice shapes observed at the IRT test (Ref. 5), as will be discussed later in Section 4.0.

1.2 Scope and Objectives

In Task 2.1 Boeing focused on two sub-tasks. The first one is a CFD analysis of the CRM65 wing-body (WB) configuration at the three nominal conditions tested at the IRT (Ref. 5). These 3D RANS-based CFD simulations were used to generate ice accretions using the LEWICE3D code. The second sub-task uses the grid models of the test articles used in the IRT to compute additional flow fields and ice shapes corresponding to test conditions. These ice shapes are compared to the ice shapes measured during the IRT test campaign.

In Task 2.2, Boeing designed a full-chord midspan model to be tested in the IRT. CFD analysis was used to compute the flow fields over the new model and evaluate the suitability of the model in matching the stagnation line locations corresponding to the WB configuration. Although results show that the full-chord model is adequate, it was determined that an addition of a flap to the model would help expand the envelope of stagnation line locations and provide a finer control over the location of the stagnation line. In order to preserve the option of testing a full-chord model, a simple-hinge, full span flap was chosen as the preferred type of flap. A set of CFD analyses were performed on the new full-chord, simple-hinge model. The resulting flow fields were used as input for LEWICE3D analysis. The resulting ice shapes were compared to those on the original WB configuration and the ice shapes measured on the corresponding hybrid models during the test campaign.

1.3 Approach

The analysis described in Tasks 2.1 and 2.2 were performed using two NASA codes. The aerodynamic simulations were executed with OVERFLOW, a 3D, URANS-based code used extensively at NASA and The Boeing Company and was also used in the previous contract, exhibiting reasonable agreement with experimental results (Figure 1.4 through Figure 1.6). In addition, the grid systems for these cases were already available and ready to be used. The ice formation analysis was executed using LEWICE3D which was also used in the previous phase of the study.

2.0 CFD Analysis of CRM65 Wing-Body Configuration

Task 2.1.1 of this contract was performed on a WB configuration of the CRM65. The un-sheared geometry definitions was utilized to perform 3D RANS calculations of three nominal conditions that were tested in the IRT. A description of the CFD simulation including geometry, grid system, and numerical scheme will be presented next followed by the flow-field results.

2.1 Geometry and Grid Setup

The geometry of the CRM65 wing was consistent with the geometry used to design the hybrid IRT models (Ref. 5). It includes an un-sheared wing definition only. The body geometry was scaled down from the original CRM designed by Boeing. An overset grid system, based on Boeing Research and Technology (BR&T) common practices, was created. The CFD simulations were performed on a half model with a symmetry plane and far-field boundary extended about 25 semi-spans away. The final grid system comprises of 11 grids and 28.6 million grid points. Multiviews of the geometry are presented in Figure 2.1.

2.2 Numerical Scheme

All the 3D RANS simulations utilized the NASA developed OVERFLOW flow solver, version 2.2k. OVERFLOW is specifically designed for a structured, overset grid system. It includes multiple options for numerical schemes and turbulence models. The current simulations were performed using an HLLC++ upwind scheme (IRHS = 6, ILHS = 6), Spalart-Allmaras (S-A) 1-equation turbulence model with rotational/curvature correction (SARC) and Quadratic Constitutive Relation (QCR). More detail about the OVERFLOW code can be found in Reference 7.

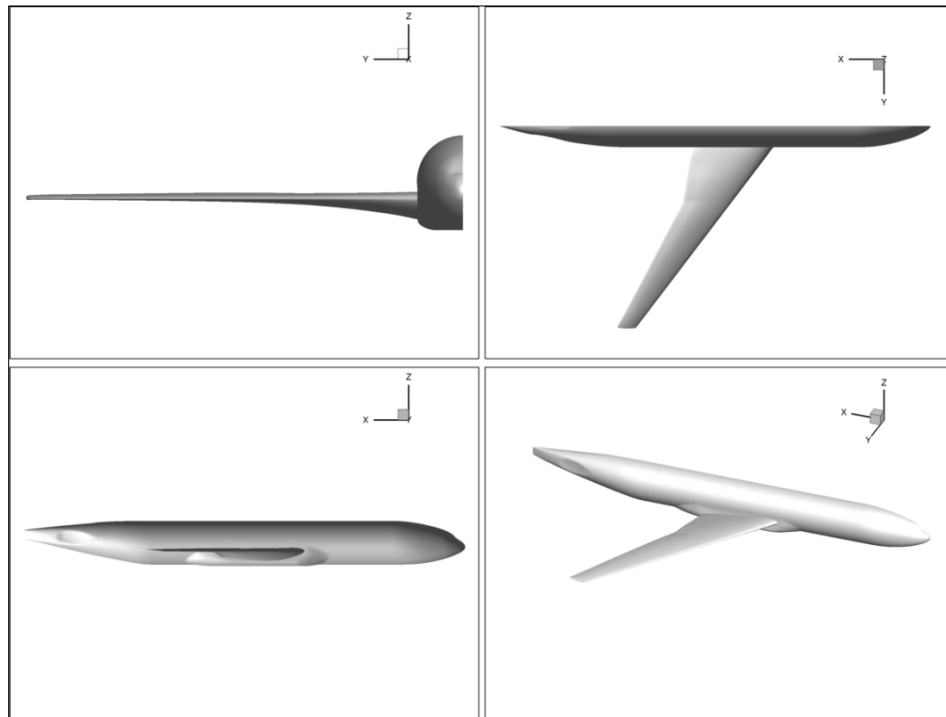


Figure 2.1.—CRM65 wing-body model.

The boundary conditions used were a no-slip condition on all solid surfaces and characteristics-based free-stream conditions at the far field. A sample of convergence characteristic for a sample case are presented in Figure 2.2. The simulation corresponds to the WB33 conditions; altitude of 10,000 ft, Mach number of 0.36, Angle of Attack (α) of 3.7° and Reynolds number of 160587.3/in. Figure 2.2(a) presents the log of the residuals of each grid in the grid system as a function of the iteration number, while Figure 2.2(b) presents the history of the lift coefficient (C_L), drag coefficient (C_D) and pitching moment coefficient (C_M) as function of iteration number. The lift and drag forces are within 0.1 percent of their final values after 10,000 iterations and the solution residuals decreased, on average, 6 orders of magnitude. Even though full convergence was achieved after 10,000 iterations, all cases ran for 20,000 iterations, using three levels of multigrid. A typical run on the BOEING HPC system, using 96 CPU's takes an average of 6 wall clock hours.

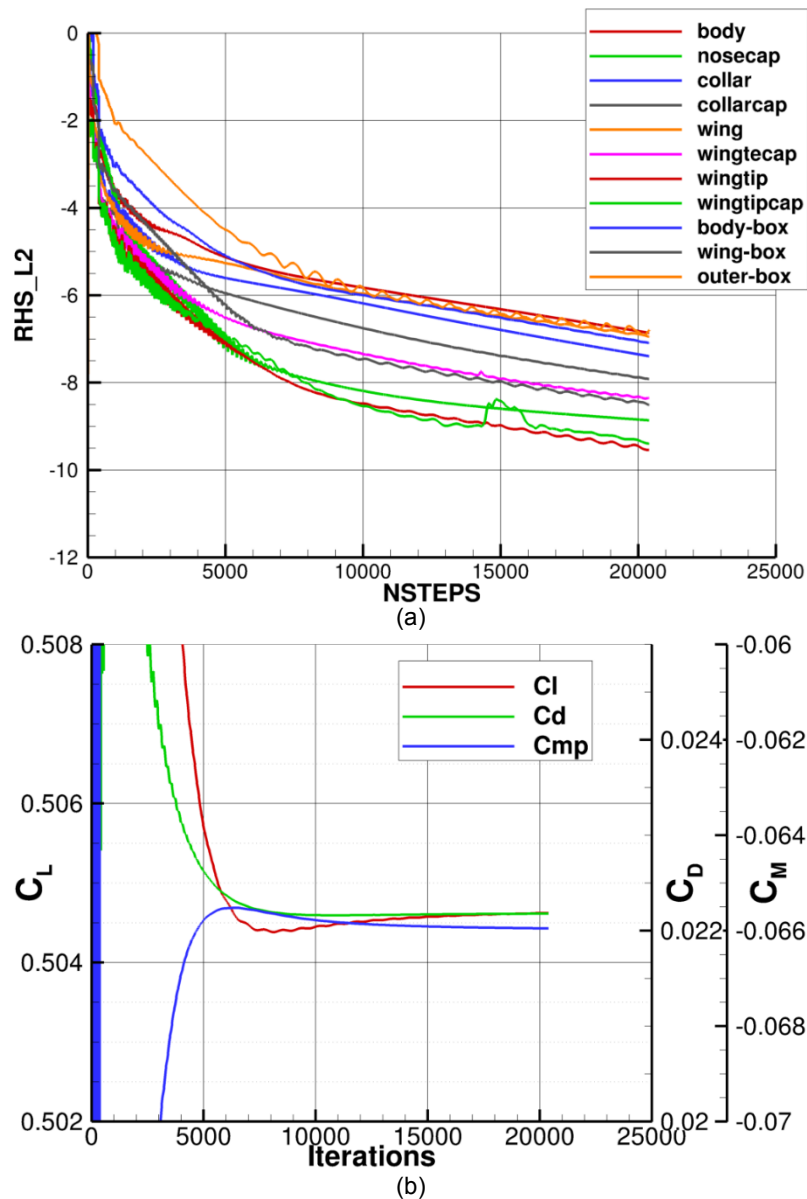


Figure 2.2.—Convergence characteristics for a sample run. (a) Residuals convergence. (b) Forces and moment convergence.

2.3 Results

The 3D RANS-based CFD analysis of the CRM65 unsheared WB configuration was performed for three flight cases (WB33, WB41, and WB52) shown in Table 2.1. An identical set of analysis was performed on the sheared WB configuration for comparison. A summary of the force and moment coefficients computed for both WB configurations are shown in Table 2.2. It is apparent that removing the shear from the wing resulted in a slight reduction on lift, 3, 1.1, and 1.3 percent for WB33, WB41, and WB52, respectively. These computed flow fields, designated as Clean Flight Baseline (CFB) were used as input for the ice accretion analysis to generate the Iced Flight Baseline (IFB) as described in Section 4.0.

2.4 Attachment Line Extraction

The size of aircraft models that can be tested in a wind tunnel is constrained by the physical size of the tunnel and its power capabilities. Since most wings found on modern aircraft are too big to fit in the NASA Icing Research Tunnel, scaling the geometry and icing conditions is needed. The ultimate goal of this scaling is to match the full scale ice shapes in the icing tunnel. Attachment line location is one of the important parameters used in attempting to match ice shapes in test conditions with full scale flight conditions because it has a first order impact on ice shape (Ref. 4). Hence, a robust and consistent method of attachment line identification it is important. There are few ways to identify the attachment line on a wing surface. For example:

- Visually—diverging surface streamlines
- Loci of maximum pressure points near the leading edge ($C_p \max$)
- Line of zero skin friction ($C_f = 0$)

The results of extracting the stagnation line using the three methods are presented in Figure 2.3 and Figure 2.4. Contours of pressure coefficient and streamlines computed on the Inboard Model (IB) used in previous IRT testing are shown in Figure 2.3 along with a yellow line representing the location of zero skin friction. It is clear that the line that connects the positions where each streamline splits and diverges away is at the same physical location of the contour line of zero skin friction. Pressure and skin friction coefficients at a midspan cut through the test article are shown in Figure 2.4. The relevant component of the skin friction is the one normal to the surface; in this configuration it is the z-component. It is clear from the plot that the chordwise (x) location of maximum pressure ($C_{p\max}$) is the same as the location of zero skin friction ($C_f = 0$). These two methods are consistent and can be used interchangeably.

TABLE 2.1.—SUMMARY OF FLIGHT CONDITIONS

Reference case	Mach number	AoA, degree	Altitude, feet	Static pressure, kPa	Static temperature, °C
WB33	0.36	3.7	10000	69.7	−4.0
WB41	0.35	4.4	5000	84.3	−6.0
WB52	0.41	2.1	5000	84.3	−6.0

TABLE 2.2.—SUMMARY OF FORCES AND MOMENT COEFFICIENTS FOR CRM WB CONFIGURATION

Case	Mach number	Sheared wing				Unsheared wing		
		AoA, degree	CL	CD	CM	CL	CD	CM
WB33	0.36	3.7	0.5202	0.02662	−0.0775	0.5046	0.02218	−0.0660
WB41	0.35	4.4	0.5802	0.02873	−0.0777	0.5736	0.02398	−0.0719
WB52	0.41	2.1	0.3845	0.02049	−0.0787	0.3794	0.01642	−0.0756

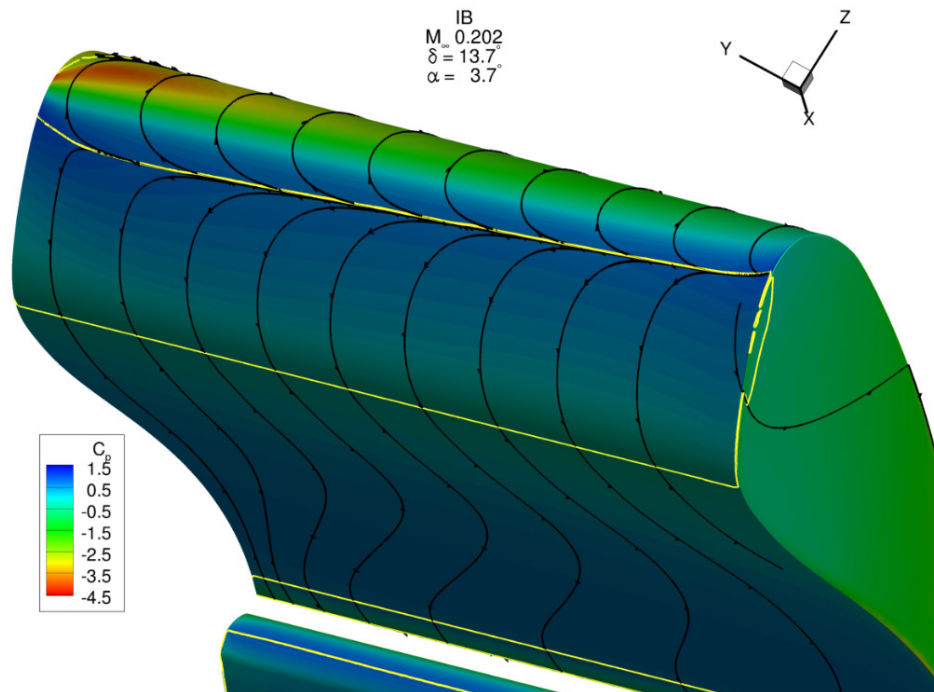


Figure 2.3.—Identification of Attachment line location by $C_f = 0$ line (in yellow) and streamlines (in black).

Look at a cut @ midspan:

- for a 3D configuration at this orientation need to plot **z-component** of skin-friction (normal to the wing)

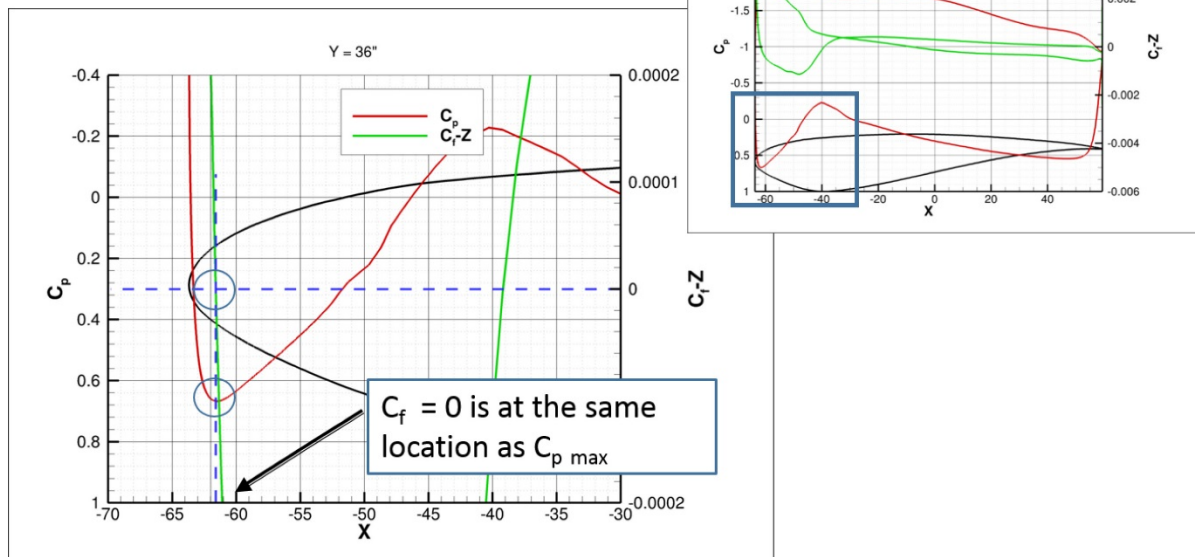


Figure 2.4.—Identification of Attachment line location by $C_f = 0$ line and $C_p \text{ max}$.

Since the only parameter measured in the wind tunnel was pressure coefficient, it was appropriate to use the $C_{p_{max}}$ method in the CFD analysis. The location of the attachment line is measured by the streamwise wrap distance (s), from the wing highlight (forward most point of the model at zero angle of attack) with positive value along the lower surface of the wing. An automated script was developed to compute the wrap distance (s). The script includes a few steps:

1. Use a TECPLOT script to extract the leading edge part of each spanwise surface grid line
2. Use a FORTRAN program to locate $C_{p_{max}}$ and compute distance in streamwise direction (s) to highlight (X_{min}) for each section
3. Fit a curve through the points

The output from the script as applied to the three cases is shown in Figure 2.5. The symbols are the exact distance to the attachment line at each span location while the lines are 3rd-order polynomial fit through the points. Note that the discontinuities in the points' distribution are due to the chordwise resolution of the grid lines at the leading edge. The attachment line locations for a cut at 64 percent span are presented in Table 2.3 for the sheared and unsheared CRM65 WB configuration.

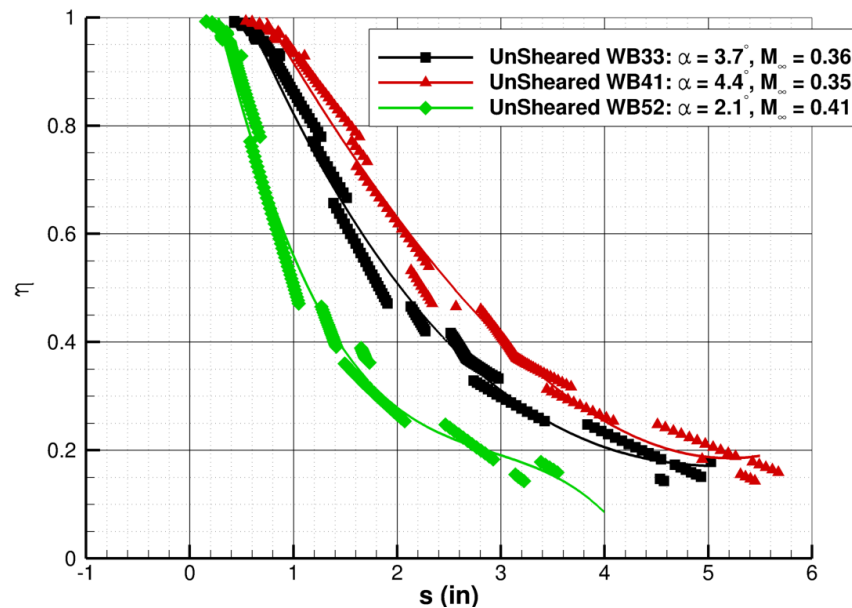


Figure 2.5.—Attachment line location across span for CRM65 WB configuration.

TABLE 2.3.—ATTACHMENT LINE LOCATIONS FOR CRM WB CONFIGURATION

Case	Mach number	AoA, degree	s (in.) at 64% span	
			Sheared wing	Unsheared wing
WB33	0.36	3.7	1.283	1.433
WB41	0.35	4.4	1.549	1.928
WB52	0.41	2.1	0.617	0.786

3.0 CFD Analysis of IRT Test Articles

The second sub-task (2.1.2) expands the scope of the previous contract *Large-Scale, Swept-Wing Test Articles Fabrication; Research and Test Support for NASA IRT* (NNC10BA05-NNC14TAA36T) by performing 3D RANS-based CFD calculation on the original IRT test articles at larger set of test conditions. These flow fields will be used to create an expanded set of ice shapes to be compared with the ones measured in the IRT.

3.1 Setup

The grid system setup for this task followed exactly the setup of the previous contract. Where grid systems were already available, the existing grids were used. Each of the three models, Inboard model (IB), Midspan model (MS) and the Outboard model (OB) were comprised of a wing and a flap. The Inboard model wing section was mounted off the tunnel floor with a gap of 1.25 in. (no modeling of the turntable and plate base) and sealed at the ceiling, while the Midspan model and the Outboard model wing section were sealed at both ends. The flap, for all models, was trimmed according to the model geometry and capped at each end. The tunnel was modeled as rectangle sized 108 by 72 by 720 in. (width by span by length). Setting up the model at a specific angle of attack can be modeled in two ways. The wing and the flap (at its desired deflection) can be rotated about the center of the turntable. An alternative way is to keep the wing at its zero angle of attack position but rotate the tunnel in the other direction. In this study the second alternative was chosen for two reasons. First, this setup is more consistent with CFD simulation in free air, where the angle of attack is controlled by rotating the freestream velocity vector and not the model itself. Second, by definition, the highlight location on the wing used in the calculation of the distance to the attachment line is the most forward point (minimum X) on the wing at zero angle of attack. Hence, when the second alternative is used, the wing is kept at the same location regardless of the angle of attack and there is no need to search for the highlight point because it is always the same grid point.

A typical grid system for the IRT model includes 17 zones and about 28 million grid points. An example of the grid system in multiple views is shown in Figure 3.1.

Boundary conditions imposed on the model as follows:

- No-slip adiabatic walls on wing and flap
- No-slip adiabatic walls on tunnel walls
- Freestream at tunnel inflow
- Outflow conditions based on Riemann invariants at the tunnel exit. These boundary conditions allow for reversed flow direction at the tunnel exit and are more stable than simple extrapolations

3.2 Results

The set of CFD runs performed for this task are summarized in Table 3.1. Consistent with the CRM65 WB calculations, all runs were performed with the one-equation S-A turbulence model and upwind numerical scheme. Better convergence was found with an initial set of 40,000 iterations using multigrid, followed by another set of 30,000 to 40,000 iterations with multigrid turned off. The number of iterations needed for convergence was dependent on the flow conditions where cases with larger flow separation needed more iterations to converge. The Reynolds numbers listed in Table 3.1 are the actual input to OVERFLOW where it is based on reference velocity and grid length unit (1 in. in all grids).

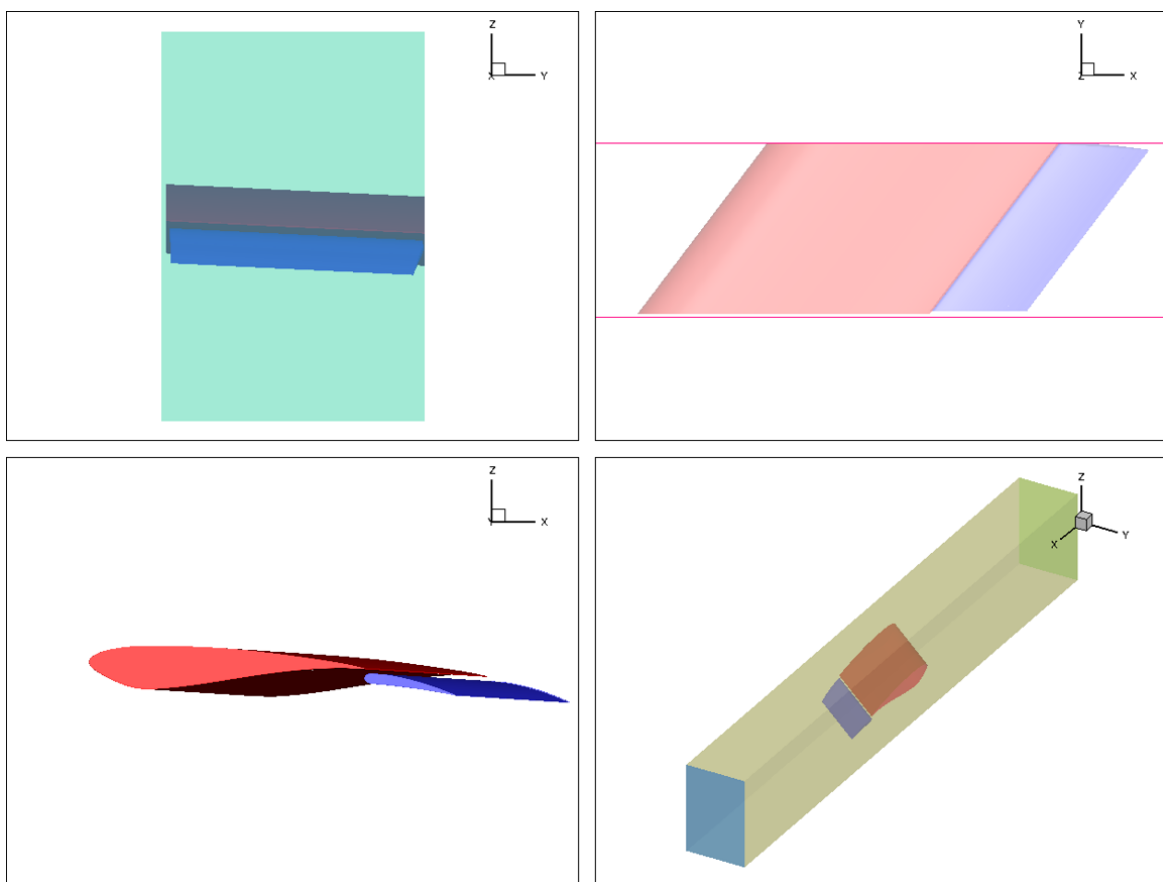


Figure 3.1.—Grid system setup for simulation in the IRT.

TABLE 3.1.—CFD RUN MATRIX FOR IRT TEST ARTICLES

Wing section	Flap deflection, degree	AoA, degree	Mach number	Reynolds number	Temperature °R
Inboard	13.7	4.4	0.21	121100.3	468.01
	13.7	2.1	0.21	121100.3	468.01
Midspan	25	3.7	0.28	162219.0	468.5
	25	3.7	0.37	162219.0	468.5
	16	2.1	0.41	162219.0	468.5
	14	2.1	0.21	162219.0	468.5
Outboard	9	2.1	0.21	145000.0	468.5
	9	2.1	0.4	145000.0	468.5
	14	3.7	0.37	145000.0	489.5

4.0 Ice Accretion Analysis for the CRM65 WB and IRT Test Articles

The flow fields computed in Tasks 2.1.1 and 2.1.2 are the basis for the ice accretion analysis as defined in Task 2.1.3. The icing conditions were set up by mutual agreement between the NASA PI and the contractor. They included an additional set of conditions not specified in the contract because of the small amount of extra work needed, once the computational process had been set up. The setup for the icing calculations followed by the resulting ice shapes for the CRM65 WB configuration and the IRT test models will be described next.

4.1 LEWICE3D Setup

The Langmuir D 7-bin drop distribution was used for the CRM65 WB configuration analysis.

For the IRT test models, three sets of drop distributions were considered for the LEWICE3D calculations:

- Papadakis 10-bin (used in the 2015 LEWICE3D analysis for the previous contract)
- Langmuir D 7-bin
- IRT (obtained from the 2015 Cloud Calibration Report (Ref. 8)), separated into 7 bins

As can be seen in Figure 4.1, neither Papadakis nor Langmuir D match the IRT 2015 Cloud Calibration drop distribution well at Mean Volumetric Diameter (MVD) of 20 μm . Hence, the IRT 2015 drop distribution, which is the most representative of the tunnel conditions during the IRT hybrid model testing, was used for the current analysis. The distribution was separated into 7 bins for MVD = 20 and 50 μm and was linearly interpolated on cumulative liquid water content (LWC) to calculate intermediate MVD's, as presented in Figure 4.2 and Table 4.1.

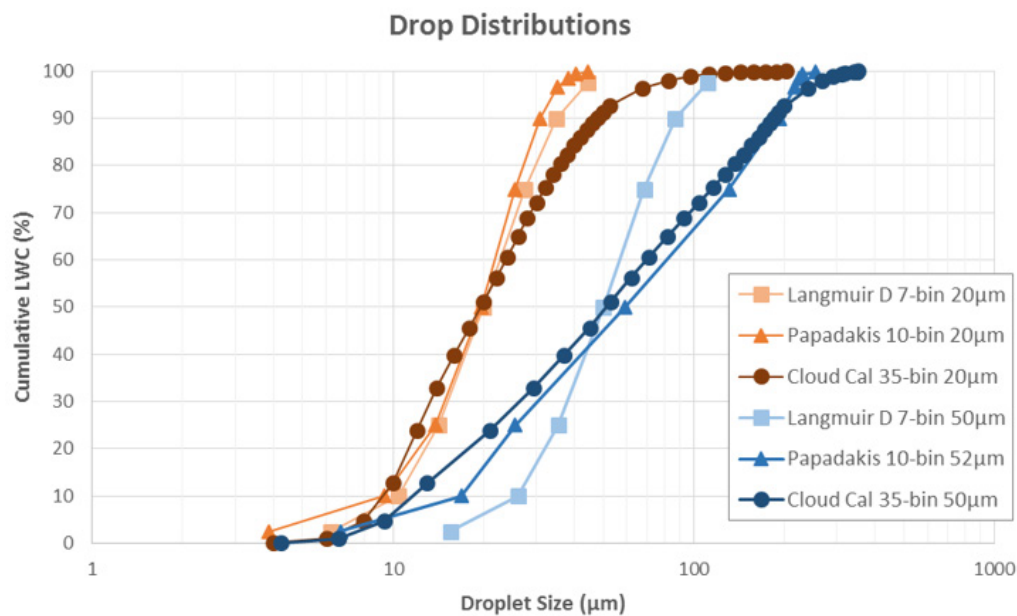


Figure 4.1.—Drop size distributions considered for LEWICE3D analysis.

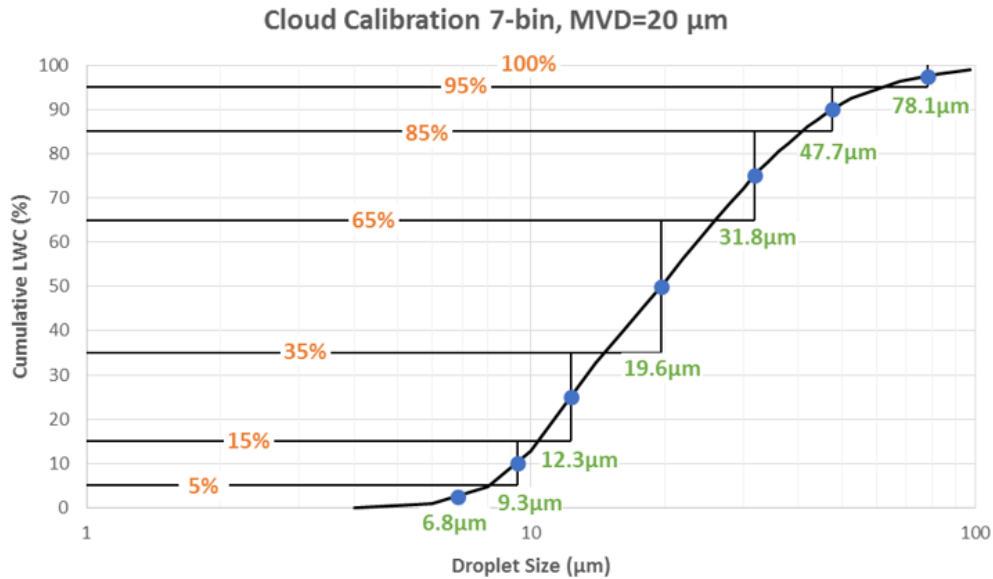


Figure 4.2.—IRT 2015 drop distribution separation into 7 bins, used in LEWICE3D analysis.

TABLE 4.1.—IRT 2015 7-BIN DROP DISTRIBUTIONS

LWC, percent	Cumulative LWC, percent	Drop sizes with MVD = 20 μm, μm	Drop sizes with MVD = 50 μm, μm
5	5	6.8	8.2
10	15	9.3	11.7
20	35	12.3	21.9
30	65	19.6	50.9
20	85	31.8	114.6
10	95	47.7	183.7
5	100	78.1	258.5

The ice density for all cases was 450 kg/m³.

The analysis utilized the Boeing version of LEWICE3D and supporting scripts, “LEWICE3D Package 3.2,” which incorporates various best practices developed for icing modeling within the Boeing Company.

4.2 Results for CRM65 Wing-Body Configuration

The set of icing conditions evaluated for the wing-body CRM65 configuration is presented in Table 4.2. These conditions are based upon App. C, where the WB33 conditions are representative of the hold flight phase at light gross weight (LGW), the WB41 conditions are representative of the hold flight phase at heavy gross weight (HGW), hence a slightly higher angle of attack, and the WB52 conditions are representative of the descent flight phase at nominal gross weight, hence the lower angle of attack and a significantly reduced exposure time to icing conditions.

Figure 4.3, Figure 4.4, and Figure 4.5 show representative ice shape results at approximately the Midspan model location, 64 percent semispan, for WB33, WB41, and WB52 temperature sweeps, respectively. The temperature sweep particularly in Figure 4.3 shows the progression between cold rime conditions to warm glaze conditions. It can be seen that for some glaze shapes as temperature increases, ice tends to extend higher on the upper surface and tends to spread thinner and farther along the lower surface. This can be seen in the difference between the WB33 T-4 and T-6 conditions in Figure 4.3, as well as the IRT Temperature Sweep warmer and mid conditions that will be presented in Section 4.3, Figure 4.6 and Figure 4.7, respectively.

TABLE 4.2.—ICING CONDITIONS FOR CRM65 WB CONFIGURATION

Case	Flight phase	Weight	AoA, degree	Static pres., kPa	Mach	TAS, knots	Total temperature, °C	Static temperature, °C	MVD, μm	LWC, g/m^3	Exposure time, minute
WB33 T-4	Hold	LGW	3.7	69.7	0.36	232	3.2	-4.0	20	0.55	45.0
WB33 T-6	Hold	LGW	3.7	69.7	0.36	231	1.1	-6.0	20	0.51	45.0
WB33 T-13	Hold	LGW	3.7	69.7	0.36	228	-6.1	-13.0	20	0.36	45.0
WB33 T-25	Hold	LGW	3.7	69.7	0.36	223	-18.4	-25.0	20	0.17	45.0
WB41 T-6	Hold	HGW	4.4	84.3	0.35	225	0.6	-6.0	20	0.51	45.0
WB41 T-13	Hold	HGW	4.4	84.3	0.35	222	-6.6	-13.0	20	0.36	45.0
WB41 T-25	Hold	HGW	4.4	84.3	0.35	217	-18.9	-25.0	20	0.17	45.0
WB52 T-6	Descent	Nominal	2.1	84.3	0.41	263	3.1	-6.0	20	0.51	4.0
WB52 T-13	Descent	Nominal	2.1	84.3	0.41	259	-4.1	-13.0	20	0.36	4.0
WB52 T-25	Descent	Nominal	2.1	84.3	0.41	253	-16.5	-25.0	20	0.17	4.1

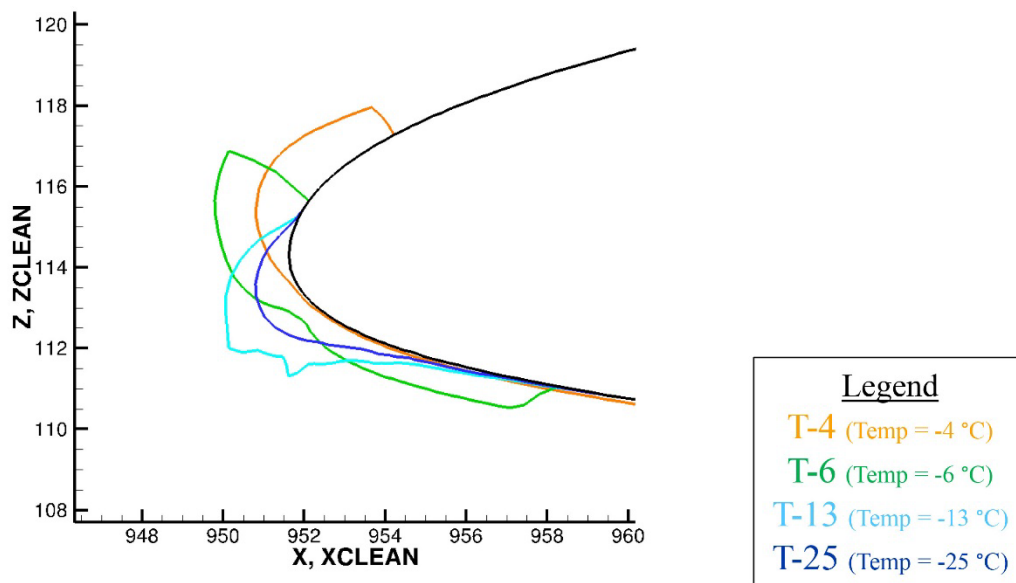


Figure 4.3.—WB33 LEWICE3D ice shapes.

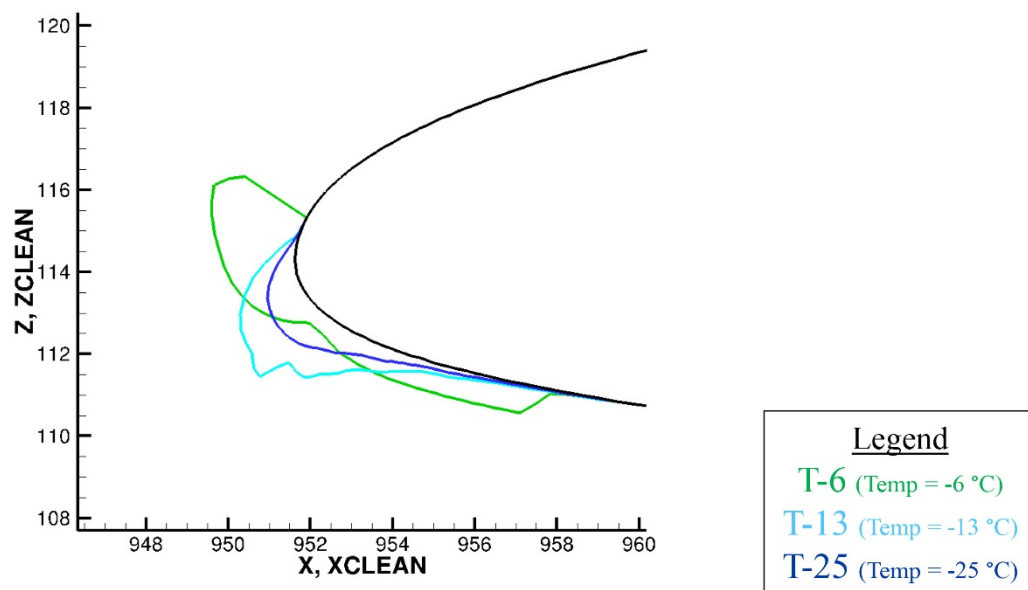


Figure 4.4.—WB41 LEWICE3D ice shapes.

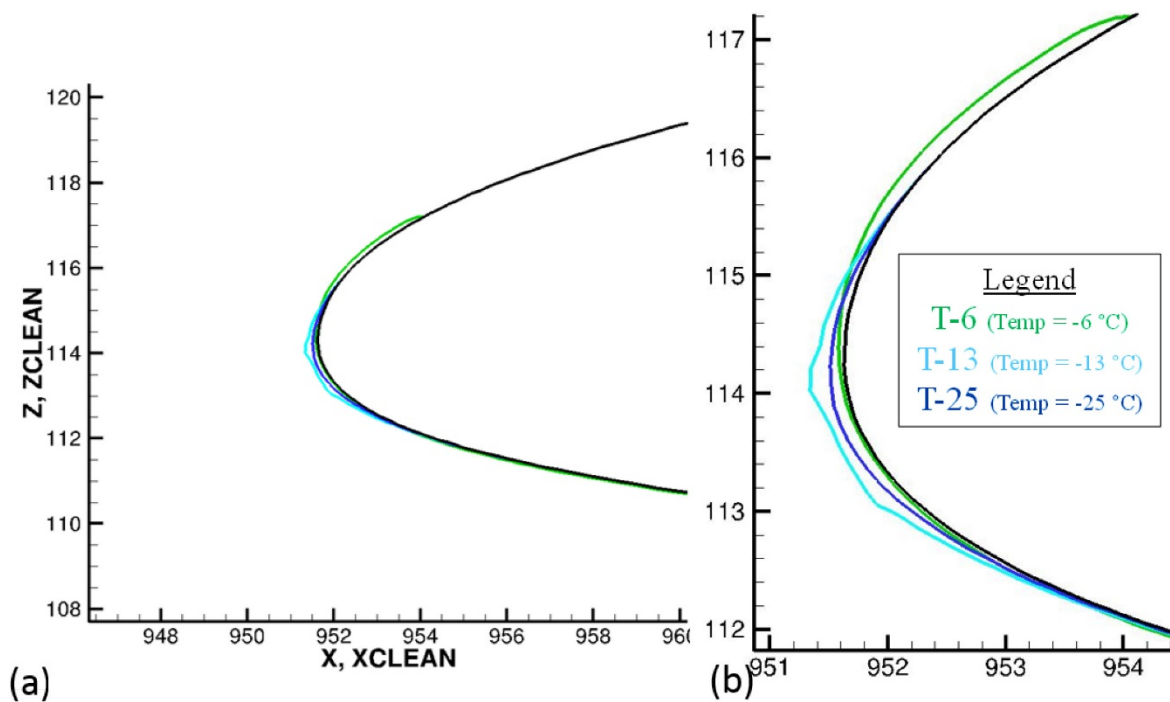


Figure 4.5.—WB52 LEWICE3D ice shapes. (a) Overall view of ice shapes. (b) Close-up view of ice shapes.

4.3 Results for IRT Test Articles

The IRT speed limitation of 130 knots and the desire to create ice accretion that is more readily suited to icing code validation led to the development of an extended set of conditions summarized in Table 4.3. These conditions represent a departure from App. C envelope used in icing certification and should not be used for certification of commercial aircraft. These icing conditions include temperature sweeps, higher and lower angles of attack (AoA), higher speed, beak ice, and WB52 T-13.

A comprehensive set of the input conditions and results is contained in the files described in Section 8.0. A comparison between the Boeing LEWICE3D ice shapes and the scanned Maximum Combined Cross Section (MCCS) ice shapes for selected runs from the IRT test are presented in the following figures. A comparison of relative aerodynamic impact between two ice shapes was made for many of the conditions described below. This was based largely on the past experience and engineering judgment of Boeing engineers involved in this project. When comparing the shapes for similar aerodynamic impact, there was a focus on upper surface horn height, upper surface ice extent, and overall interpretation of how similarly the shapes would degrade lift performance.

TABLE 4.3.—ICING CONDITIONS FOR CRM65 WB CONFIGURATION

Ice type	Run no.	Repeat run no.	AoA, degree	Flap, degree	Speed, knots	Ps, psia	Ts, °C	MVD, μm	LWC, g/m ³	Spray time, minute	Mach number	Alt., feet
Inboard Model												
Temperature sweep	TG2418	TG2409	3.7	13.8	129	13.77	−3.7	25.0	1.00	29.0	0.20	1767
	TG2408	-----	3.7	14.1	129	14.01	−17.3	25.0	1.00	29.0	0.21	1316
	TG2415	TG2412	3.7	14.1	130	14.08	−26.2	25.0	1.00	29.0	0.21	1168
Higher AoA	TG2417	-----	4.4	13.8	129	13.75	−3.7	28.0	1.00	25.5	0.20	1808
	TG2416	-----	4.4	13.8	129	13.73	−8.6	25.0	1.00	25.5	0.20	1839
Lower AoA	TG2420	-----	2.1	14.0	130	13.91	−6.1	25.0	1.00	29.0	0.20	1501
	TG2419	-----	2.1	13.9	130	13.89	−8.6	25.0	1.00	29.0	0.20	1542
WB52 T-13 ^a	TG2430	-----	2.1	14.1	130	14.05	−3.0	34.0	1.23	4.0	0.20	1229
Midspan Model												
Temperature sweep	TH2464	TH2446	3.7	24.9	129	13.93	−3.6	25.0	1.00	29.0	0.20	1458
	TH2431	-----	3.7	25.0	129	14.05	−17.5	25.0	1.00	29.0	0.21	1229
	TH2459	TH2447	3.7	25.0	129	13.80	−26.2	25.0	1.00	29.0	0.21	1708
Lower AoA	TH2457	-----	2.1	14.0	130	13.80	−6.1	25.0	1.00	29.0	0.20	1714
	TH2448	-----	2.1	14.1	128	13.65	−8.6	25.0	1.00	29.0	0.20	2012
Higher speed	TH2461	-----	3.7	25.0	181	13.50	−18.0	22.0	0.40	25.6	0.29	2308
	TH2444	-----	3.7	24.8	179	13.57	−6.3	24.0	0.65	32.2	0.28	2161
Beak ice	TH2443	-----	2.1	15.9	257	12.82	−7.4	21.0	0.37	40.3	0.41	3674
WB52 T-13 ^b	TH2437	-----	2.1	15.9	257	12.82	−14.7	21.0	0.36	4.0	0.41	3663
WB52 T-13 ^c	TH2436	-----	2.1	14.1	129	13.99	−12.5	27.0	0.71	4.0	0.20	1352
Outboard Model												
Temperature sweep	TI2487	TI2463	3.7	14.0	130	14.02	−3.7	25.2	1.00	29.0	0.20	1291
	TI2464	-----	3.7	13.9	130	13.97	−17.4	25.2	1.00	29.0	0.21	1375
	TI2480	TI2467	3.7	14.2	129	13.87	−26.2	25.2	1.00	29.0	0.21	1582
Lower AoA	TI2483	-----	2.1	9.1	130	13.93	−6.2	25.2	0.99	29.0	0.20	1457
	TI2481	TI2473	2.1	9.1	130	13.91	−8.7	25.2	1.00	29.0	0.20	1497
Higher speed	TI2489	-----	3.7	14.2	231	13.10	−8.0	20.0	0.55	18.0	0.36	3099
	TI2494	-----	3.7	14.1	232	13.09	−18.4	19.9	0.30	25.3	0.37	3118
Beak ice	TI2475	-----	2.1	8.9	248	13.00	−7.0	21.9	0.38	30.0	0.39	3305
WB52 T-13 ^b	TI2474	-----	2.0	9.0	247	12.97	−14.4	20.9	0.38	4.0	0.39	3357
WB52 T-13 ^c	TI2472	-----	2.1	9.0	131	13.90	−12.5	26.9	0.71	4.0	0.21	1519

^aIncorrect scale

^bReference

^cScale

Figure 4.6, Figure 4.7, and Figure 4.8 present the results of a temperature sweep at otherwise constant conditions for the Inboard, Midspan, and Outboard hybrid models. At the warmer temperature (-3.7°C) the LEWICE3D shape does not match the MCCS shape as well because the LEWICE3D ice shapes extend too high along the upper surface. (Ice shapes extending too high along the upper surface result in an overly-conservative maximum lift decrement for a wing.) As the temperature gets colder the ice shape match improves significantly. At a temperature of -17.4°C the shapes are considered a better match due to the similarity of aerodynamic impact between them, in spite of the presence of horns on the LEWICE3D shape. At the -26.2°C temperature the shapes are also a better match due to the similarity of aerodynamic impact even though there are differences in thickness on the lower surface. Figure 4.9 presents a comparison of the entire temperature sweep for both the LEWICE3D and the MCCS shapes.

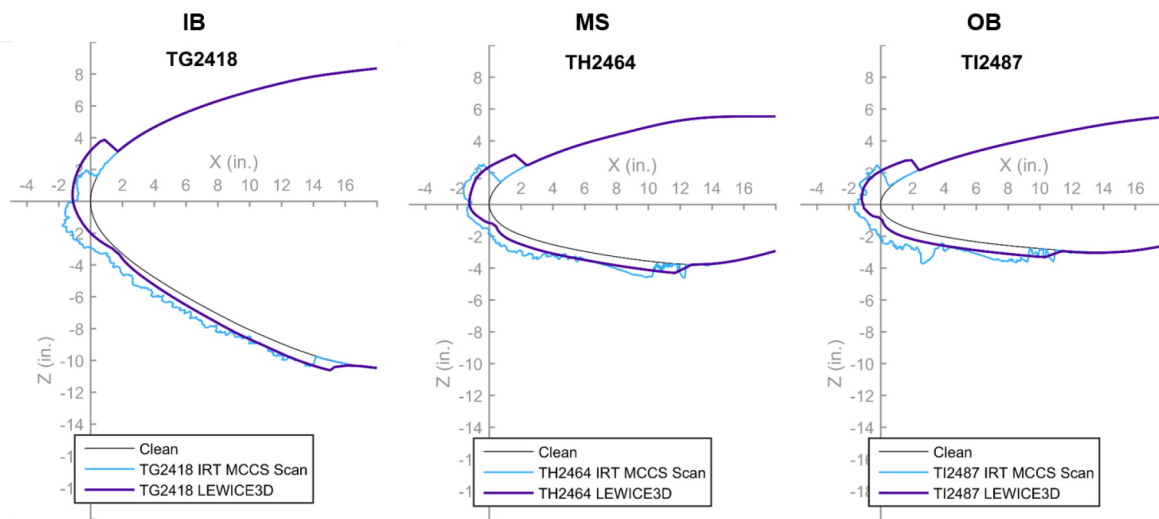


Figure 4.6.—Temperature sweep, warmer -3.7°C .

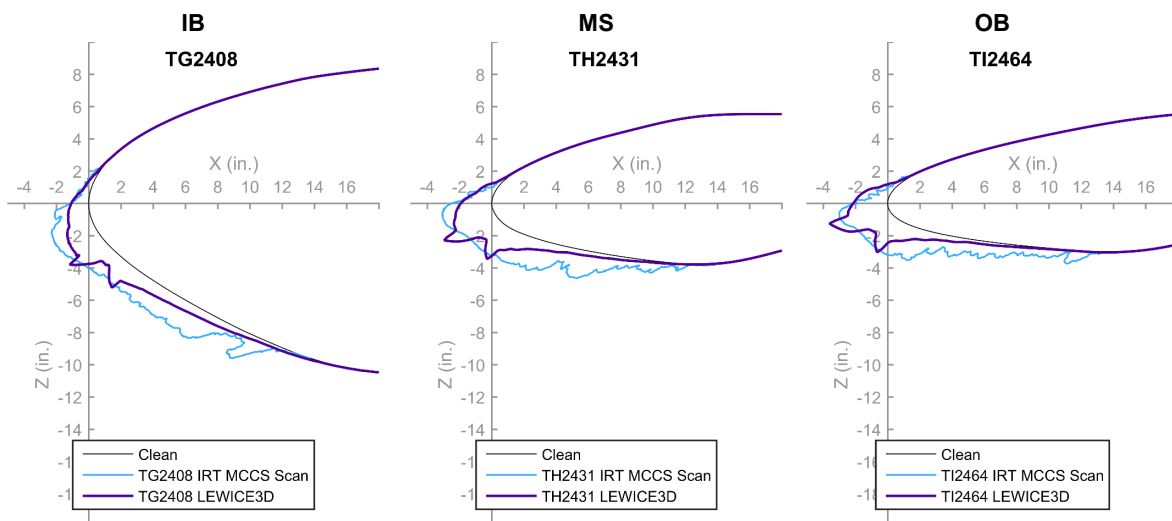


Figure 4.7.—Temperature sweep, mid -17.4°C .

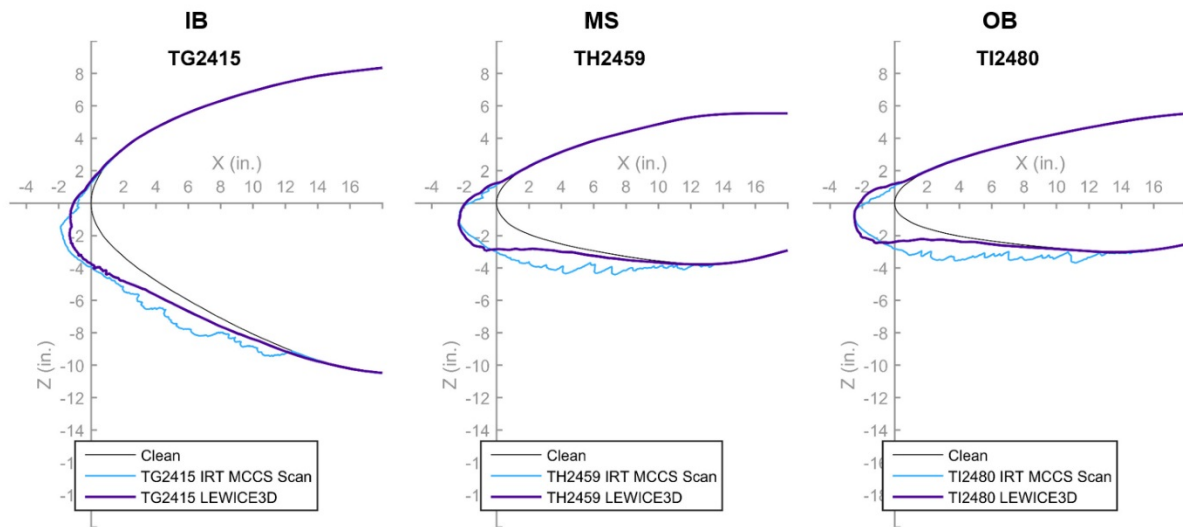


Figure 4.8.—Temperature sweep, colder -26.2°C .

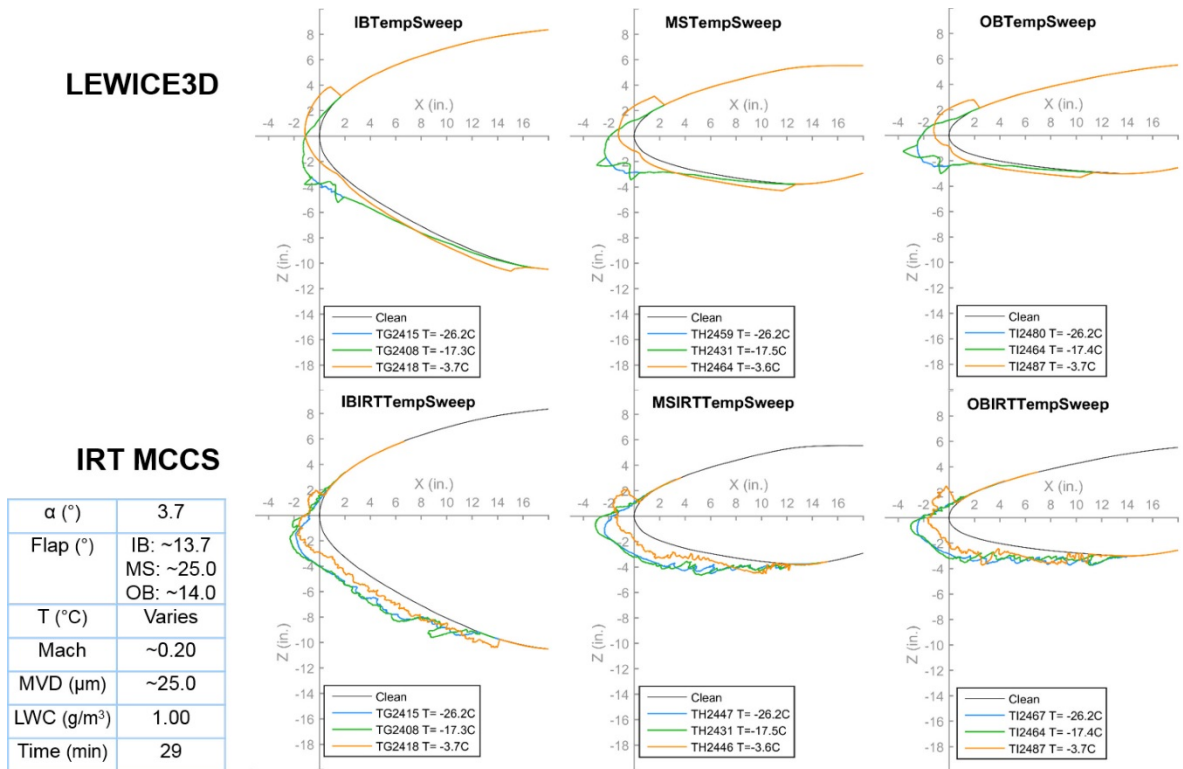


Figure 4.9.—Ice shape comparison for temperature sweep conditions.

A comparison of Inboard model ice shapes at higher angle of attack for two temperatures is presented in Figure 4.10 and Figure 4.11. At the colder temperature (-8.6°C) the shapes are considered a better match because they are expected to have similar aerodynamic impact. The IRT ice shape may have been feathered on the lower surface, which is not fully captured by the MCCS would account for the discrepancy in lower surface extent. At the warmer temperature (-3.7°C) the shapes do not match as well because the LEWICE3D shape extends too high on the upper surface. Figure 4.12 presents a comparison between the two temperatures for both the LEWICE3D and the MCCS shapes.

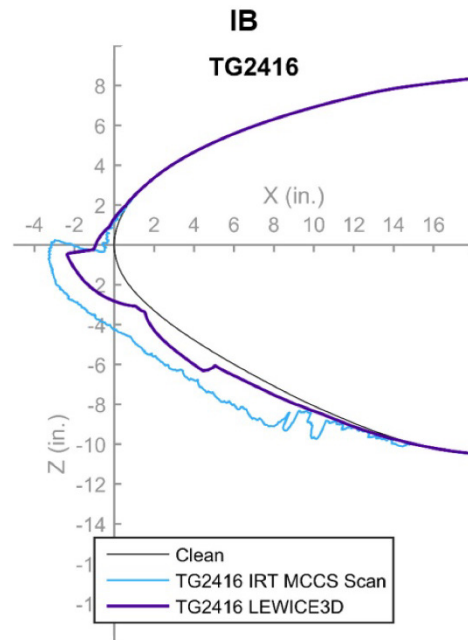


Figure 4.10.—Higher AoA, colder -8.6°C .

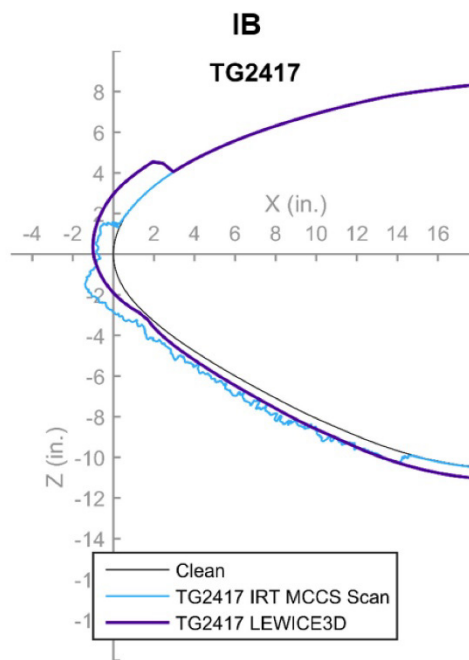
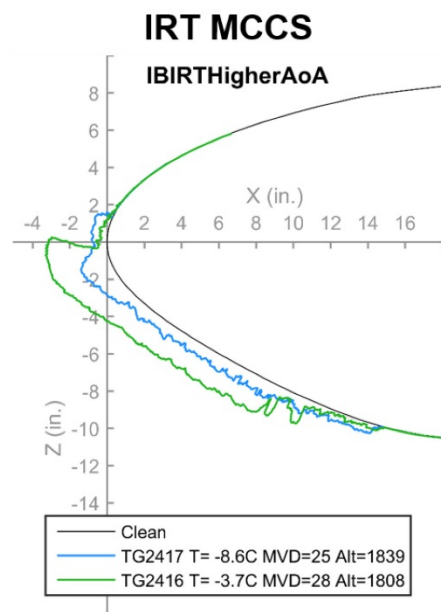
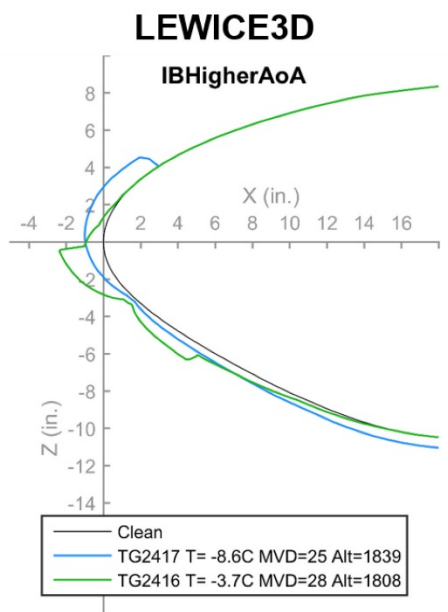


Figure 4.11.—Higher AoA, warmer -3.7°C .



α (°)	Flap (°)	T (°C)	Mach	MVD (μm)	LWC (g/m^3)	Time (min)
4.4	IB: ~13.7	Varies	0.20	Varies	1.00	25.5

Figure 4.12.—Ice shape comparison for higher AoA conditions.

Lower angle of attack conditions at two different temperatures are presented in Figure 4.13 and Figure 4.14. In this case there is a good match between the ice shapes due to expected similar aerodynamic impacts. Figure 4.15 presents a comparison between the two temperatures for both the LEWICE3D and the MCCS shapes.

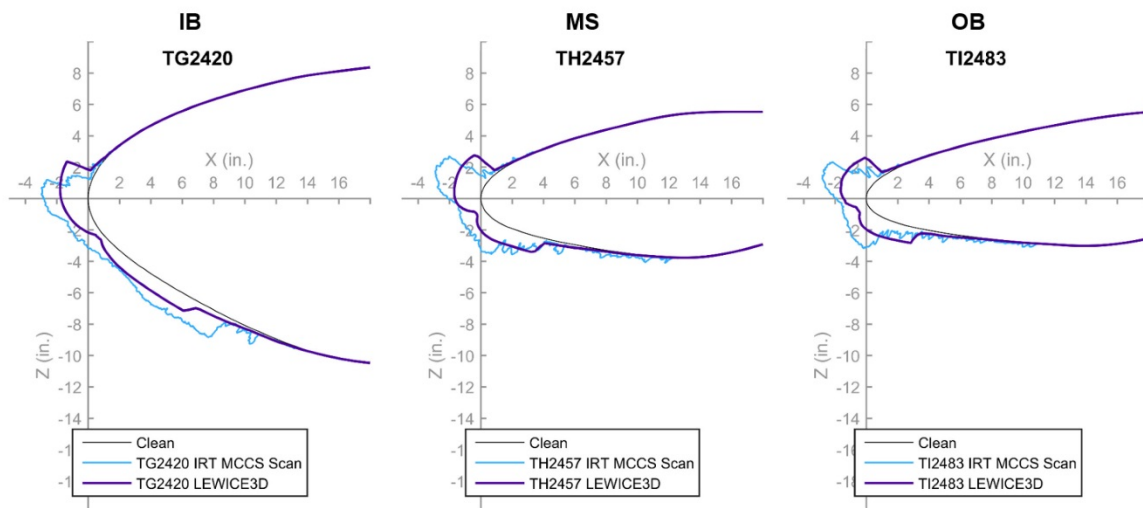


Figure 4.13.—Lower AoA, warmer -6.1 °C.

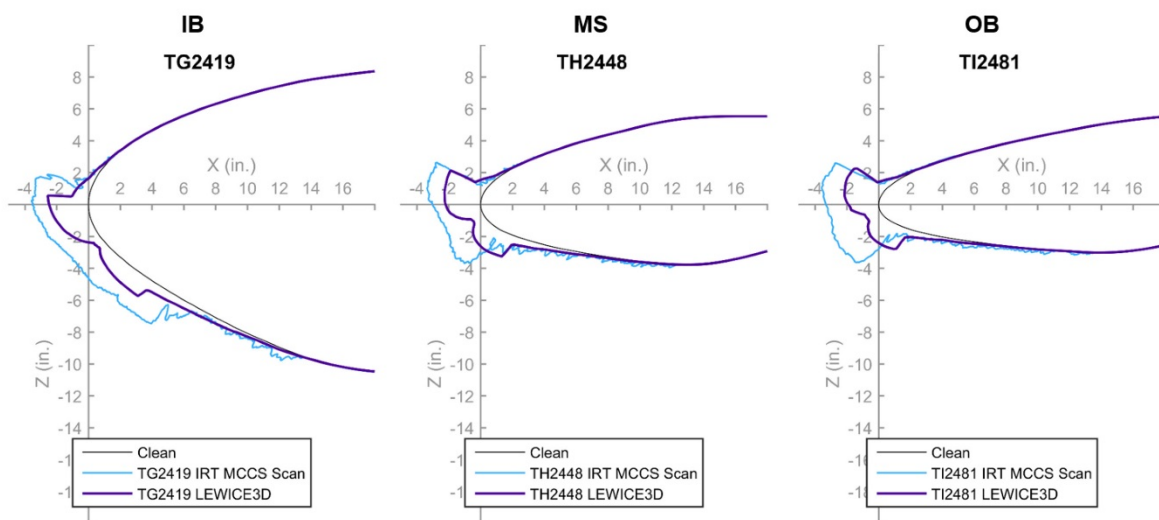


Figure 4.14.—Lower AoA, colder -8.6 °C.

LEWICE3D

IRT MCCA

α (°)	2.1
Flap (°)	IB: ~13.7 MS: ~14.0 OB: ~9.0
T (°C)	Varies
Mach	0.20
MVD (μm)	~25.0
LWC (g/m^3)	1.00
Time (min)	29

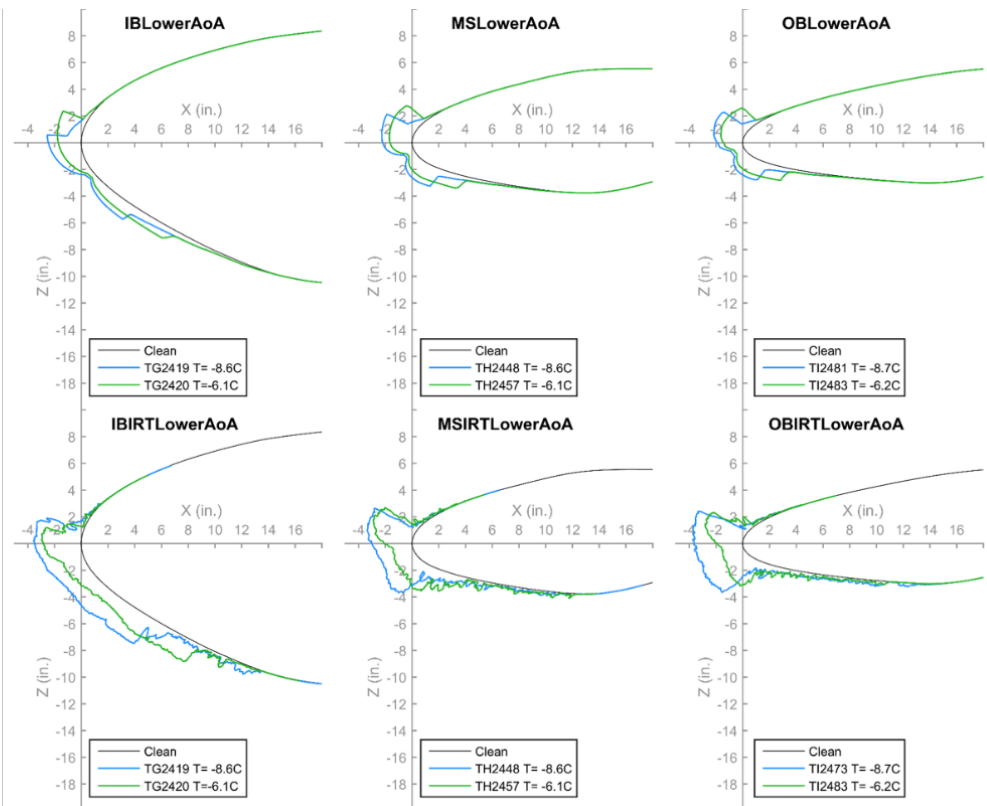


Figure 4.15.—Ice shape comparison for lower AoA conditions.

Higher speed shapes at two different temperatures are presented in Figure 4.16 and Figure 4.17. At the colder condition ($-18.0\text{ }^{\circ}\text{C}$) the shapes match well. At the warmer condition ($-6.3\text{ }^{\circ}\text{C}$) the Midspan model shapes do not match as well due to the higher upper horn extent, but the Outboard model shapes do match due to the similarity in aerodynamic impact between the two shapes. Figure 4.18 presents a comparison between the two temperatures for both the LEWICE3D and the MCCS shapes.

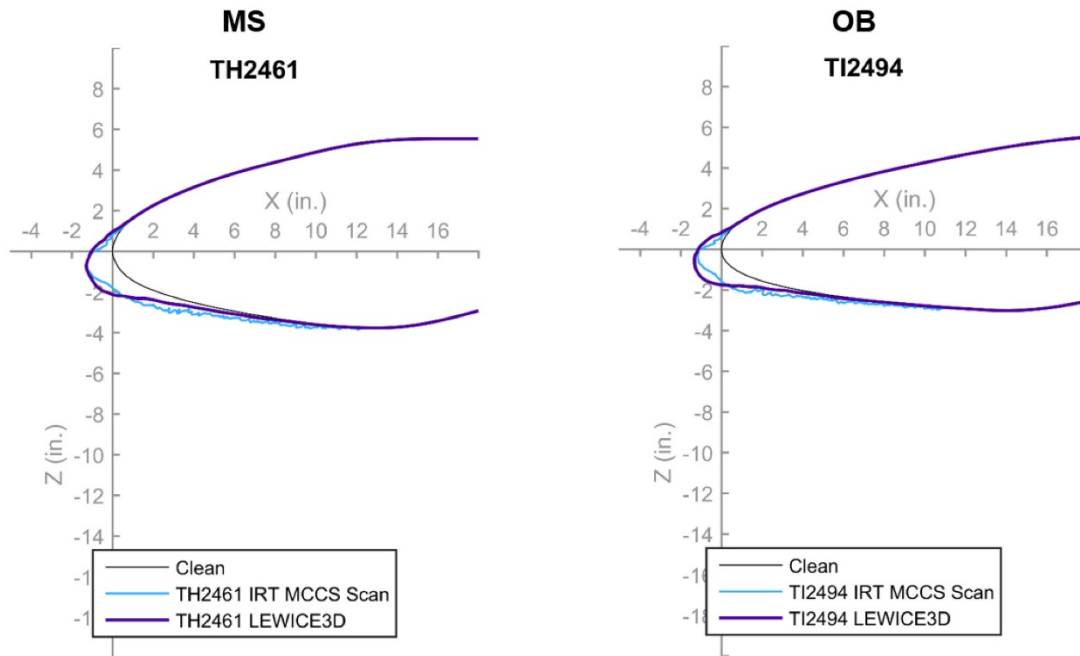


Figure 4.16.—Higher speed, colder $-18.0\text{ }^{\circ}\text{C}$.

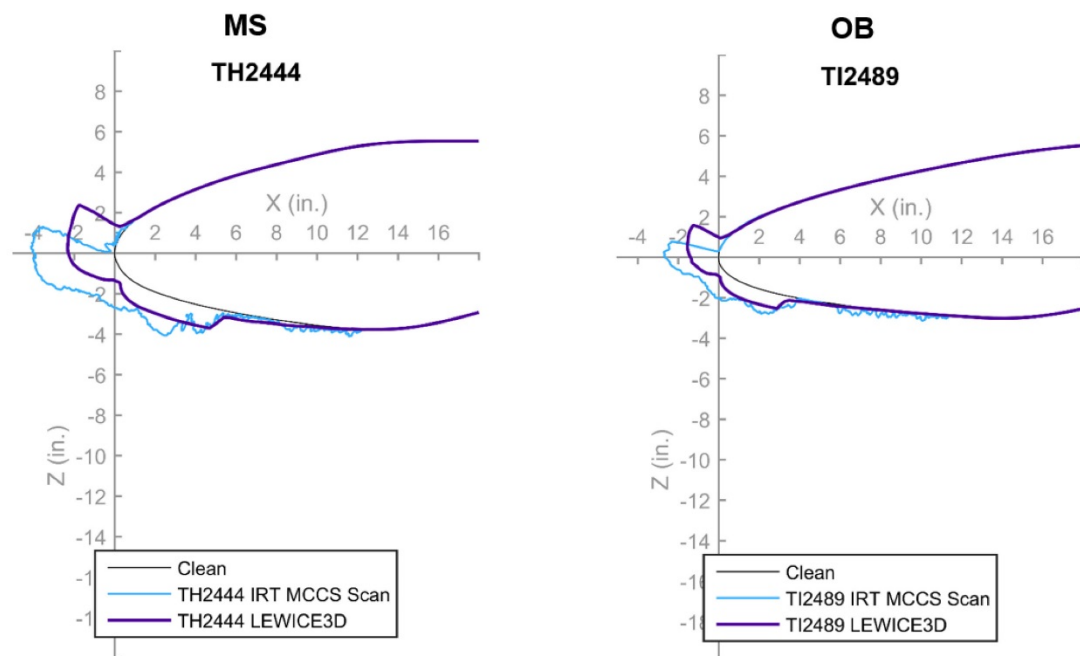


Figure 4.17.—Higher speed, warmer $-6.3\text{ }^{\circ}\text{C}$.

LEWICE3D

IRT MCCS

α (°)	3.7
Flap (°)	MS: ~25.0 OB: ~14.0
T (°C)	Varies
Mach	MS: ~0.28 OB: ~0.36
MVD (μm)	Varies
LWC (g/m^3)	Varies
Time (min)	Varies

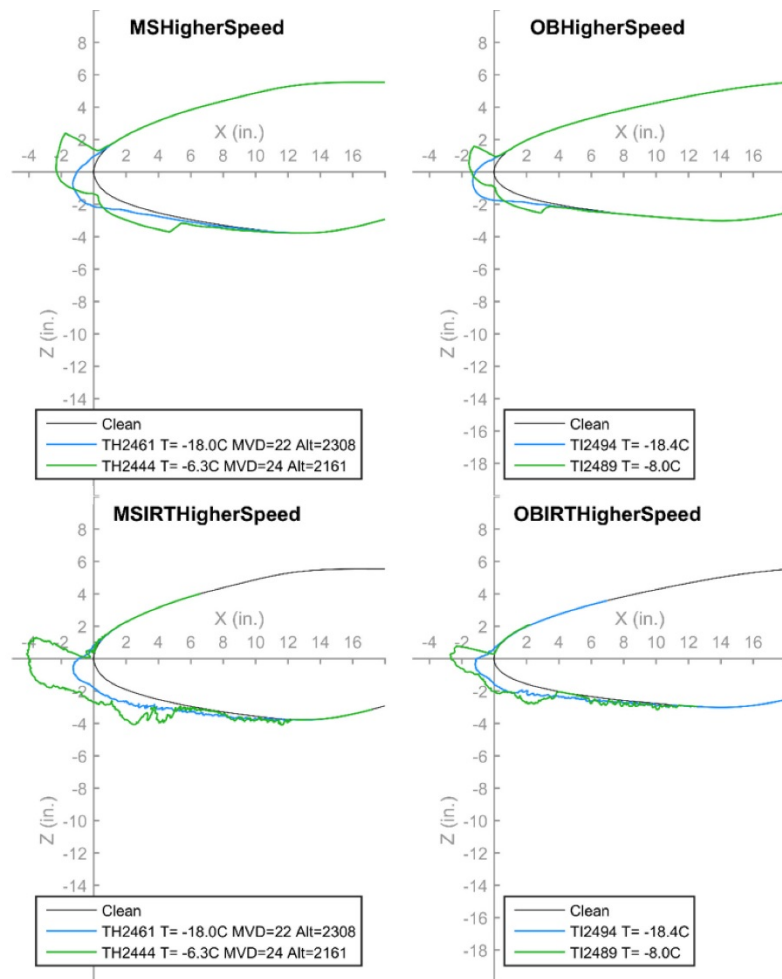


Figure 4.18.—Ice shape comparison for higher speed conditions.

The comparison for beak ice is shown in Figure 4.19. It can be seen that there is a significant mismatch between the LEWICE3D and MCCS ice shapes. In an attempt to find the source of the discrepancy, a set of increasing temperature conditions was analyzed in LEWICE3D for the OB model. The results presented in Figure 4.20 show that the modeling of beak ice does not improve with an increase in temperature. This has been recommended as a future improvement to the LEWICE3D tool.

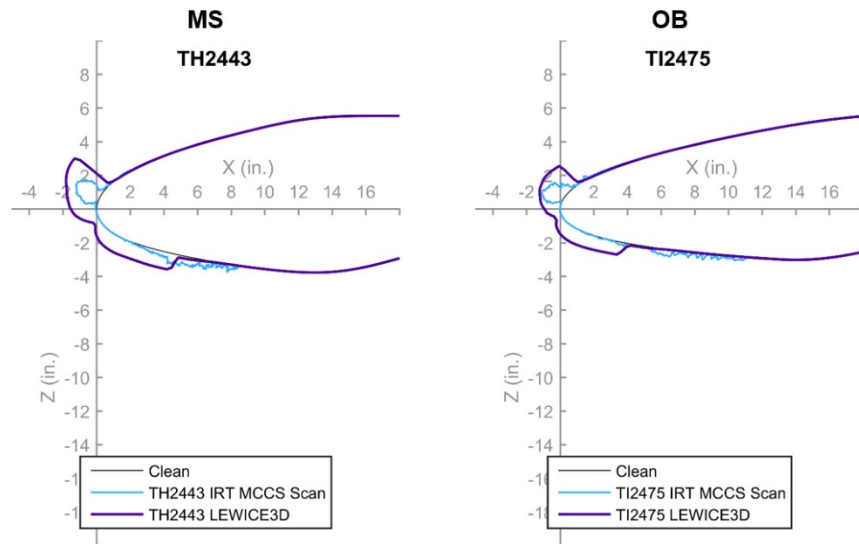


Figure 4.19.—Beak ice shapes.

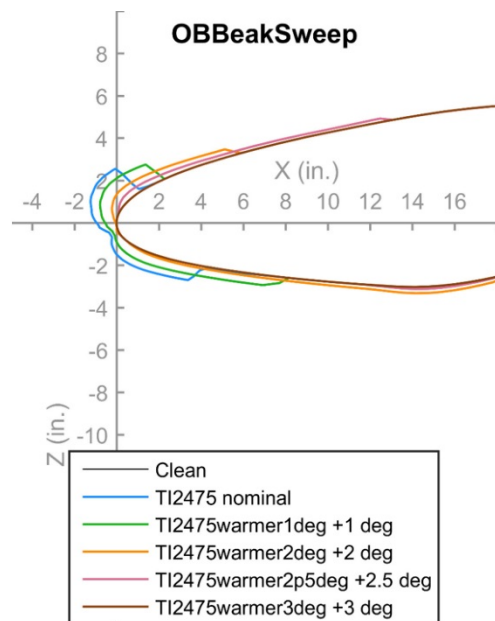


Figure 4.20.—Beak ice temperature sweep.

The next set of results for the WB52 T-13 scale and reference conditions are presented in Figure 4.21 and Figure 4.22. The Inboard scale condition shapes match well, but the Midspan and Outboard models of both conditions do not match as well due to the over prediction of horns by LEWICE3D. Figure 4.23 presents a comparison between the two conditions for both the LEWICE3D and the MCCS shapes.

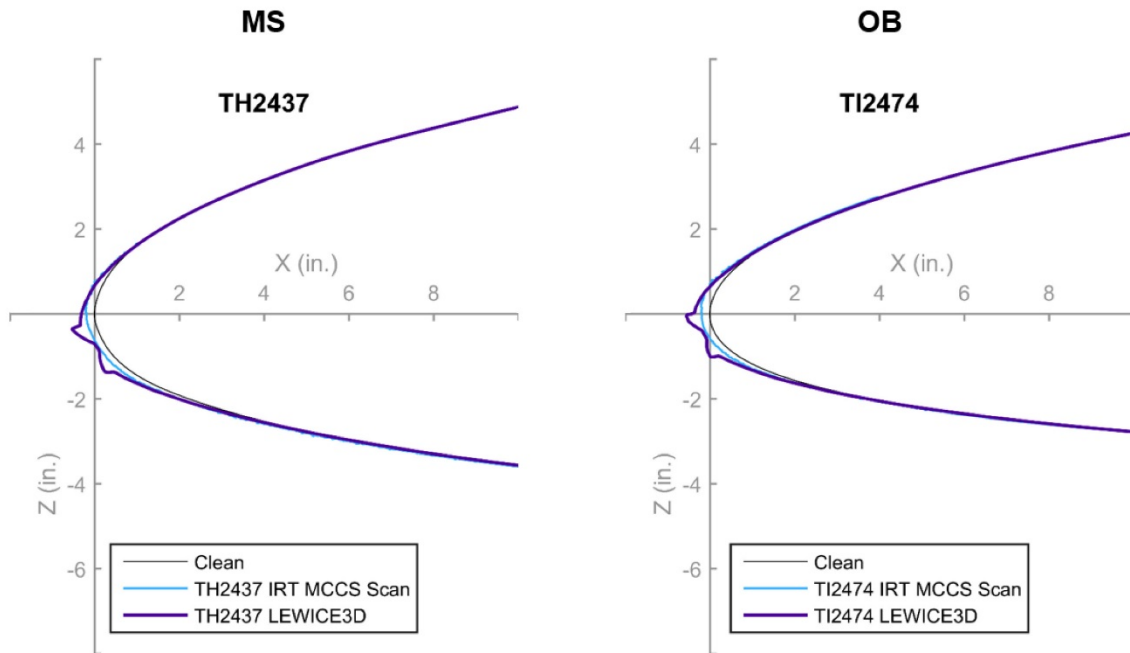


Figure 4.21.—WB52 T-13, reference.

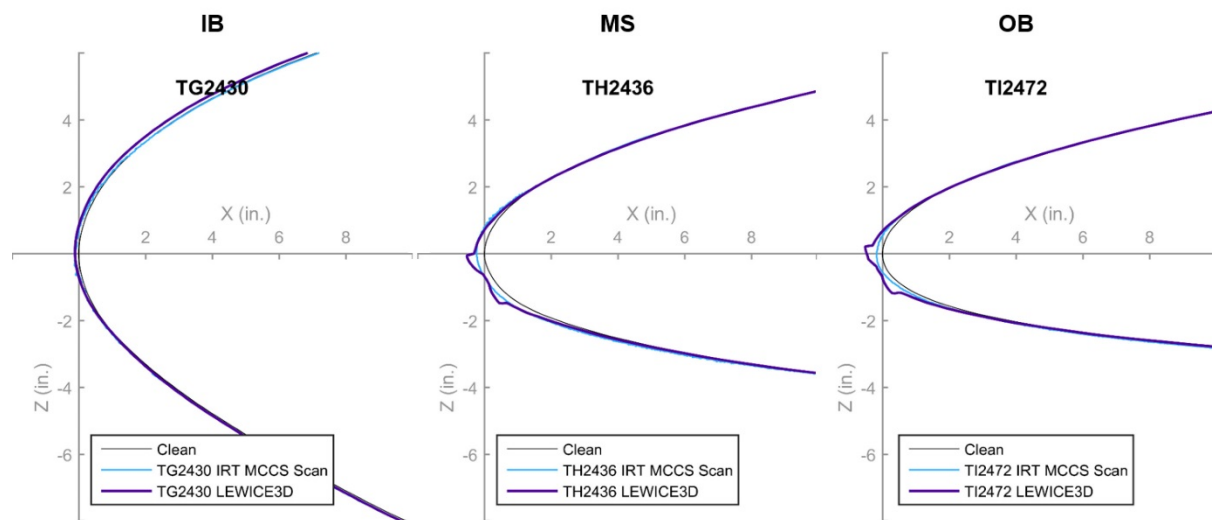


Figure 4.22.—WB52 T-13, scale.

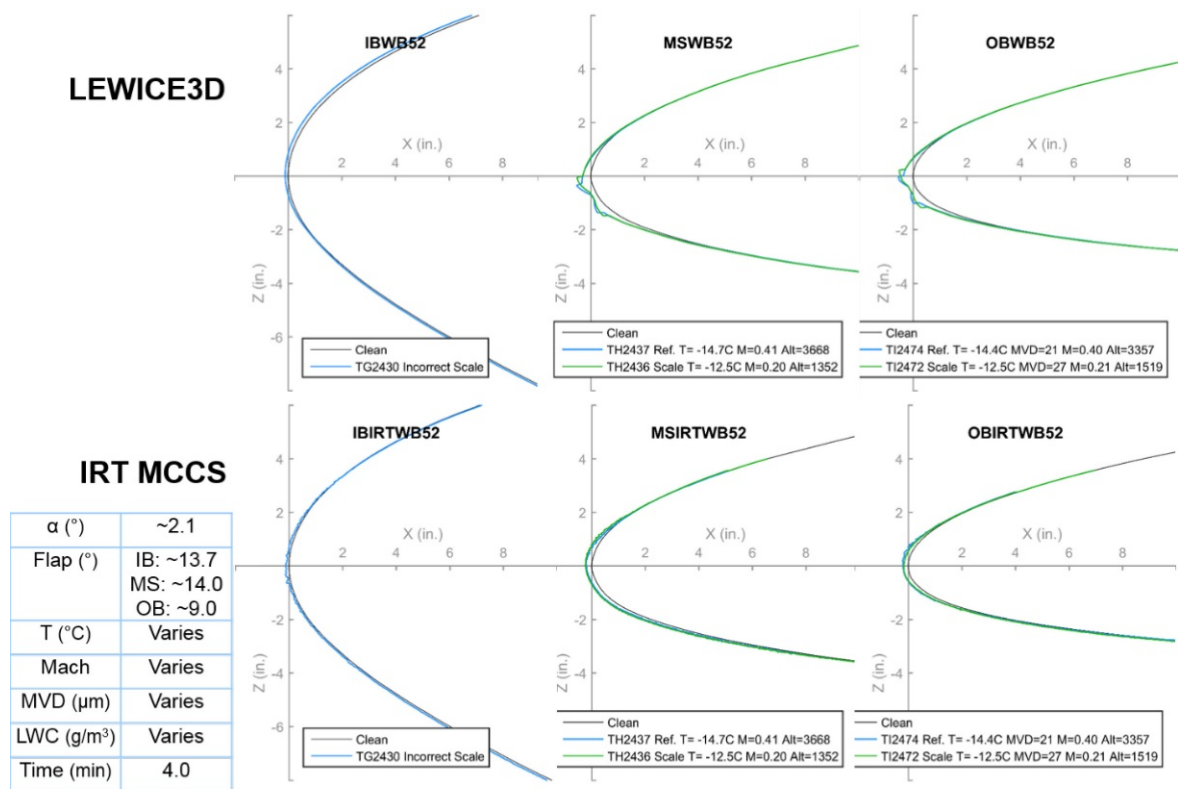


Figure 4.23.—Comparison of ice shapes for WB52 T-13 conditions.

Figure 4.24 and Figure 4.25 repeat some of the previous ice shapes to show additional MCCS scans from repeat runs in the IRT. These show that there was good repeatability of the IRT icing runs when comparing the maximum combined cross section shapes.

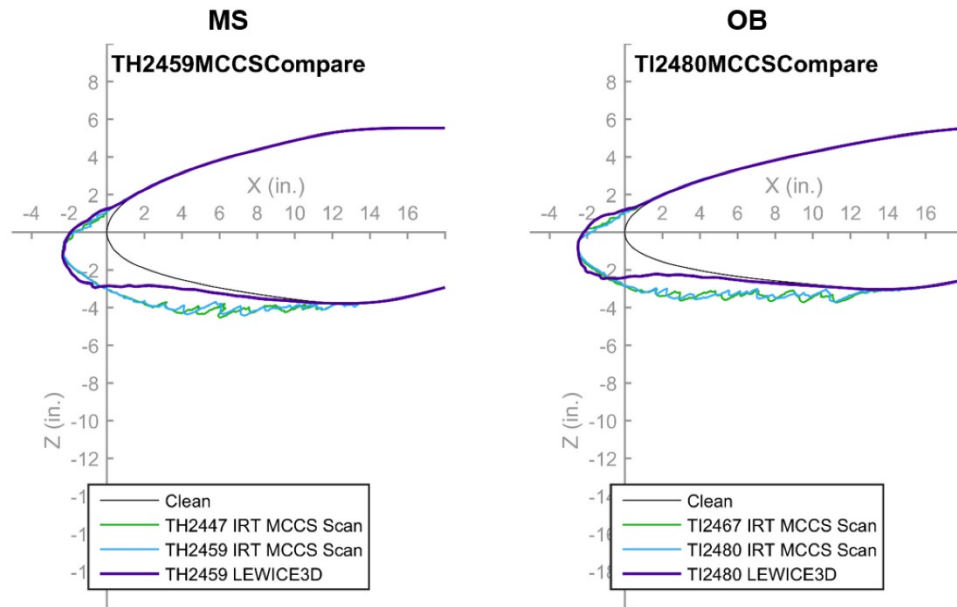


Figure 4.24.—IRT repeat runs of the cold temperature sweep at -26.2°C .

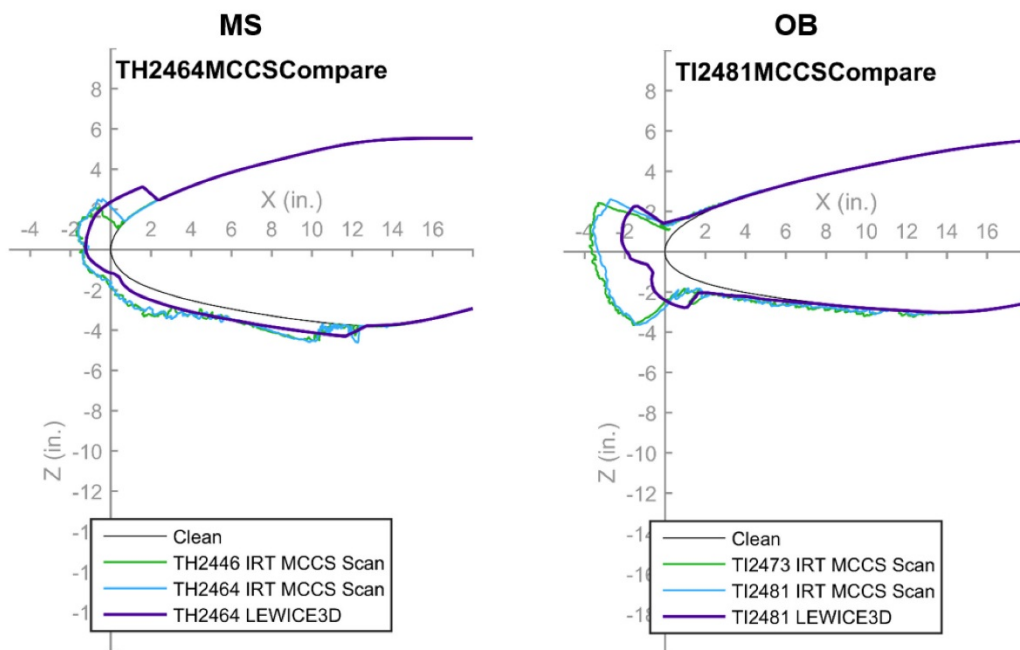


Figure 4.25.—IRT repeat runs of the warm temperature sweep at -3.7°C (left) and the cold lower AoA condition at -8.6°C (right).

The last set of calculations look at the sensitivity of ice shapes to the type of drop size distribution used in the LEWICE3D calculations. The three sets of distributions described in Section 4.1 are used and results are shown in Figure 4.26 for the “WB52 T-13 Scale” condition and Figure 4.27 for the “Higher AoA, Cold -8.6°C ” conditions respectively. For the first case, the sensitivity of the ice shape to the drop distribution is minimal. The ice shapes presented in Figure 4.27 on the left show that the Papadakis and Langmuir D distributions create ice shapes that are similar to each other, but are significantly smaller and are worse matches to the MCCS shape than the one created by the IRT Cloud Calibration. This demonstrates the importance of running LEWICE3D with drop distributions that are representative of tunnel conditions when making direct icing tunnel to LEWICE3D comparisons. The ice shapes in Figure 4.27 on the right show that the IRT Cloud Calibration 7-bin approximation created ice shapes are very similar to the ones computed with the full 35-bin raw data. This allows LEWICE3D to be run significantly faster for a small tradeoff in ice shape prediction accuracy.

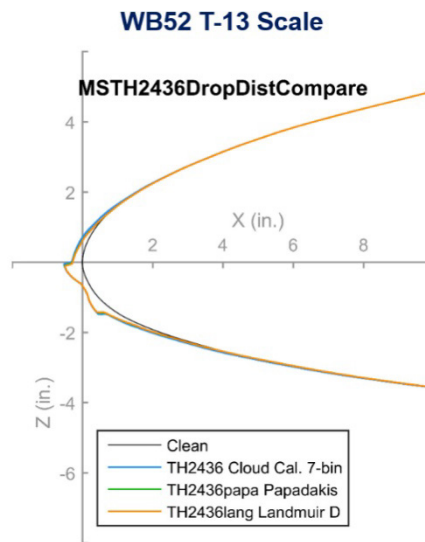


Figure 4.26.—Ice shapes sensitivity to drop distribution for midspan model run TH2436.

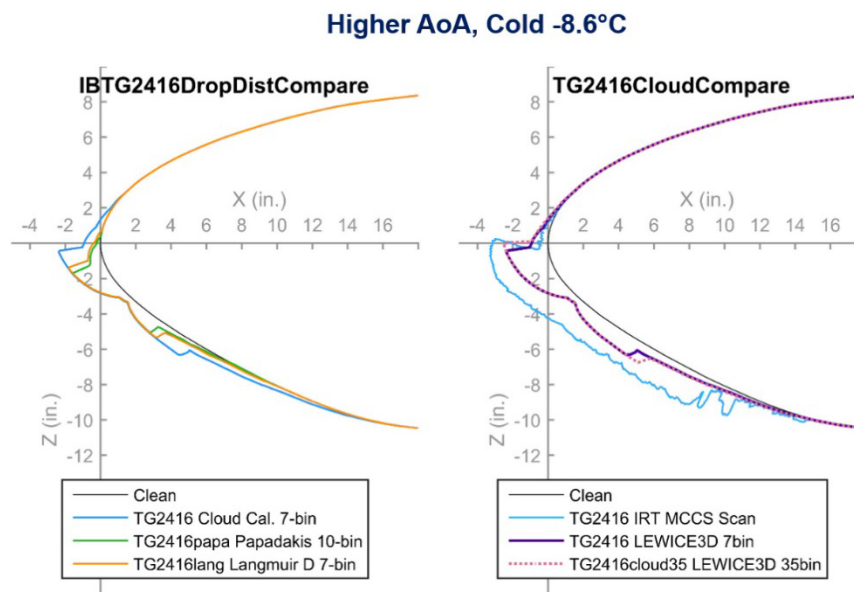


Figure 4.27.—Ice shapes sensitivity to drop distribution for inboard model run TG2416.

4.4 Ice Shape Comparison Exercise

As a follow-up activity to the IRT hybrid model LEWICE3D analysis, an exercise was coordinated to make formal comparisons between the experimental and simulated ice shapes. The goal of the exercise was to consolidate the IRT hybrid model ice shape comparisons from 2015 and Section 4.3 into one document, identify and discuss ice shape match assessment criteria, and determine how well the LEWICE3D simulations match IRT scanned MCCS ice shapes.

Boeing, NASA, the University of Washington, the University of Illinois, and the FAA rated the ice shapes separately with either “yes” or “no” responses. The responses were compiled together to facilitate team discussions and brought to light the many different perspectives held by the participating parties in the project. Conclusions included:

- Match criteria are difficult to define and often subject to engineering judgment.
- LEWICE3D-computed ice shapes match the hybrid model ice shapes generally well.
- Comparing LEWICE3D to MCCS ice shapes is difficult because of the way MCCS shapes are defined. The maximum combined sections may not be representative of the singular cuts derived from LEWICE3D.
- The IB hybrid model in the IRT performed well at many conditions in light of its large size when compared to its respective LEWICE3D simulations.

5.0 Full-Scale Midspan Model Design for the IRT

The second task (Task 2.2) in this study focused on the design of a new test article for the IRT. Previous models tested at the IRT were hybrid-type models; a truncated section where only a portion of the leading edge was a full-scale representation of the wing section, with an additional flap at the aft portion to control the flow field at the leading edge. While a full-scale test article based on the Inboard Model would not fit in the test section, the dimensions of the Midspan Model test article present an opportunity for another evaluation of the hybrid model concept; create a full-scale model of the wing section and evaluate the ice shapes formed with those of the hybrid model and the full Wing-Body configuration.

The new article will be based on a full-scale section of the CRM65 wing extracted at a midspan location. The following sections will describe Task 2.2.1 to 2.2.6 on the process of generating the test article, the CFD analysis performed, followed by a description of the design of a simple-hinged flap to allow for a fine control of the leading edge flow. The performance envelope of the new model and its optimal location in the test section were analyzed by CFD. A set of CFD flow fields corresponding to the conditions tested with the MS test article were computed and were used in the analysis of ice accretion on the new model.

5.1 Geometry Design Process

The new full-scale model was based on sectional, cut normal to the leading edge, of the CRM65 wing taken at 64 percent semispan. This location was the location used for the MS test article built for the first phase of this contract described in Section 1.1. A 3-D geometry has been created by extruding this section along a leading edge sweep line of 37.25° which corresponds to the leading-edge sweep of the CRM65 wing and limiting it to the span of the IRT test section of 72 in. The new wing section was capped at planes located 1.25 in. above the test section floor and 0.25 in. away from the ceiling and positioned on the turntable similar to the installation of the MS test article (e.g., Leading edge of model near the floor is 62 in. upstream of the center of the turntable). This geometry process is shown in Figure 5.1. The final grid system for the new model had 11 zones and 23 million grid points.

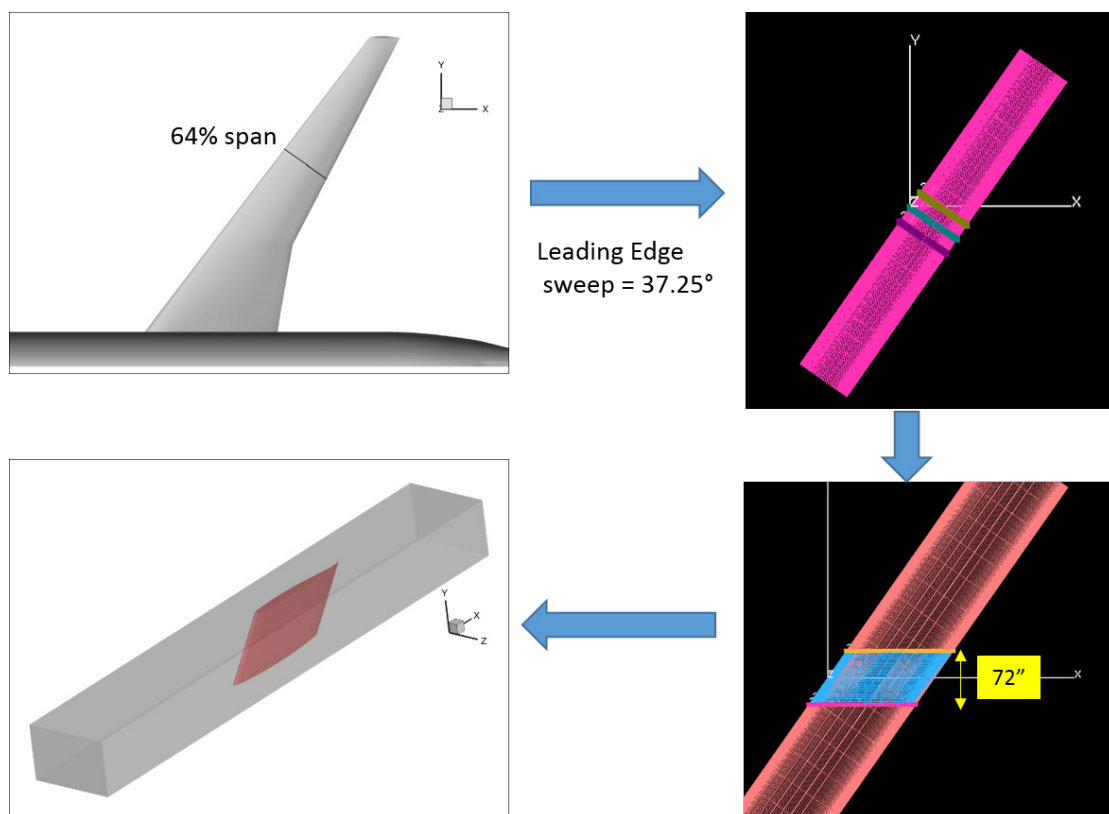


Figure 5.1.—Process of generating the full-chord test article.

5.2 CFD Analysis of Full Scale Midspan Model

In order to assess the suitability of the full-scale model, described in Section 5.1, a series of 3-D RANS-based CFD calculations were performed at a range of Mach numbers and angles of attack. All the numerical simulations utilized the OVERFLOW flow solver and followed the same setup described in Sections 2.2 and 3.1. The Mach numbers used corresponded to the nominal flight conditions shown in Table 1.1. An additional set of runs were performed at $M_\infty = 0.32$ as a backup in case the large model created excessive blockage, therefore reducing the available speed levels.

Most cases were run for more than 20,000 iterations to ensure an adequate convergence of forces. An example of the convergence histories of lift for a sample angles of attack at Mach number of 0.36 is presented in Figure 5.2. All cases converge in less than 15,000 iterations except for the case of $\alpha = 10^\circ$. The oscillations of lift in the high angle of attack case is due to a massive flow separation at the outboard part of the model (near the tunnel ceiling). Since all simulations were performed in a nontime accurate mode it was deemed prudent to assess the possibility that a time-accurate calculation is more appropriate for the cases with large flow separation and oscillatory solution. A case with a large amplitude oscillations, $M_\infty = 0.41$ and $\alpha = 10^\circ$, was chosen as a test case to assess the effect of time-accuracy on the flow-field. The natural choice of a time scale for these types of flow is the time it takes a fluid particle to travel over the model chord. Based on the flow conditions ($M_\infty = 0.41$), the freestream speed of sound ($a_\infty = 1116$ ft/sec) and the model chord length ($C = 155$ in.) the time to travel over the chord can be define as follows:

$$\text{Time} = L/u = C/u = C/(M_\infty a_\infty) = (155/12)/(0.41 \cdot 1116) = 0.028 \text{ sec.}$$

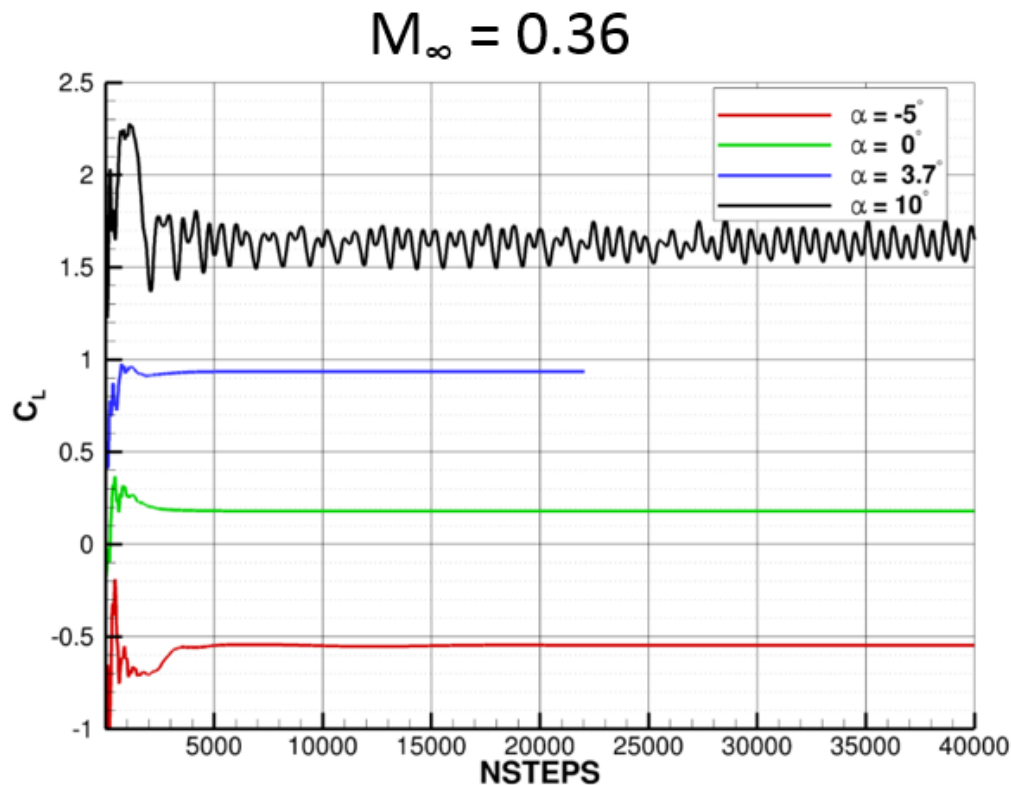


Figure 5.2.—Force convergence histories for full-scale model.

A nondimensional time step of $DTPHYS = 0.1$ was used in the simulation; with this time step it takes 1,500 iterations for a fluid particle to move across the model. The history of forces and moments as function of time is presented in Figure 5.3. Note that the time accurate solution used the nontime accurate solution as initial conditions ($T < 0$) and was run for a time of 0.4 sec, corresponding to a particle traveling across a length equivalent to about 14 chords. It is clear that the time accurate calculations reduced significantly the size of the flow separation and the oscillation in the forces and moment. The effect on the flow field can be seen in Figure 5.4, where the nontime accurate solution is shown in Figure 5.4(a) and the time-accurate flow field is shown in Figure 5.4(b). Note the reduction in flow separation, presented as an iso-surface of $u = -0.00001$, after 0.4 sec. The reduced separation resulted also in increased lift and drag as seen in Figure 5.3.

The large physical size of the model represents some challenges for the wind tunnel test. Beside the possibility of reduced levels of flow velocity due to blockage, the large model might impose high loads and moments on the turntable on which it will be mounted. As a reference, the chord on the full-scale model is comparable to the chord of the IB model described in Section 3.1. Forces and moments on the full-scale model at a range of Mach numbers and angles of attack are presented in Figure 5.5. It is apparent that at the higher Mach number ($M_\infty > 0.35$) and higher angles of attack ($\alpha > 7^\circ$) the loads would exceed the turntable load limits of 13,750 lbs and pitching moment of 10,000 lbs-ft. It is also clear the present location of the model on the turntable is unacceptable due to the high pitching moments and the model will have to be moved upstream to reduce these moments. The exact location of the model on the turntable will be discussed in Section 5.4.

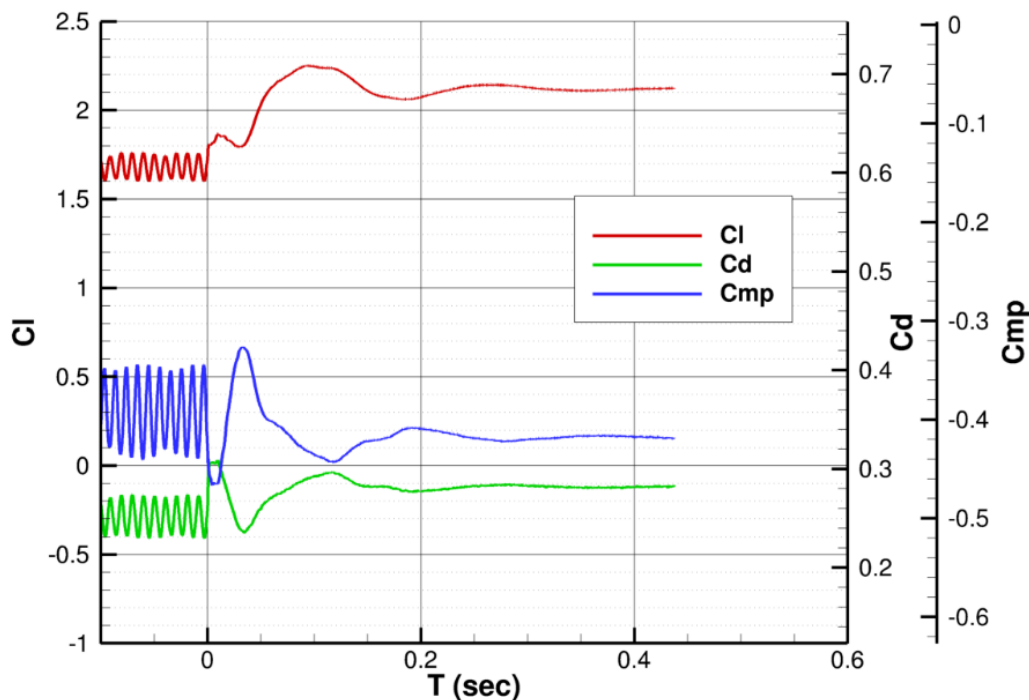
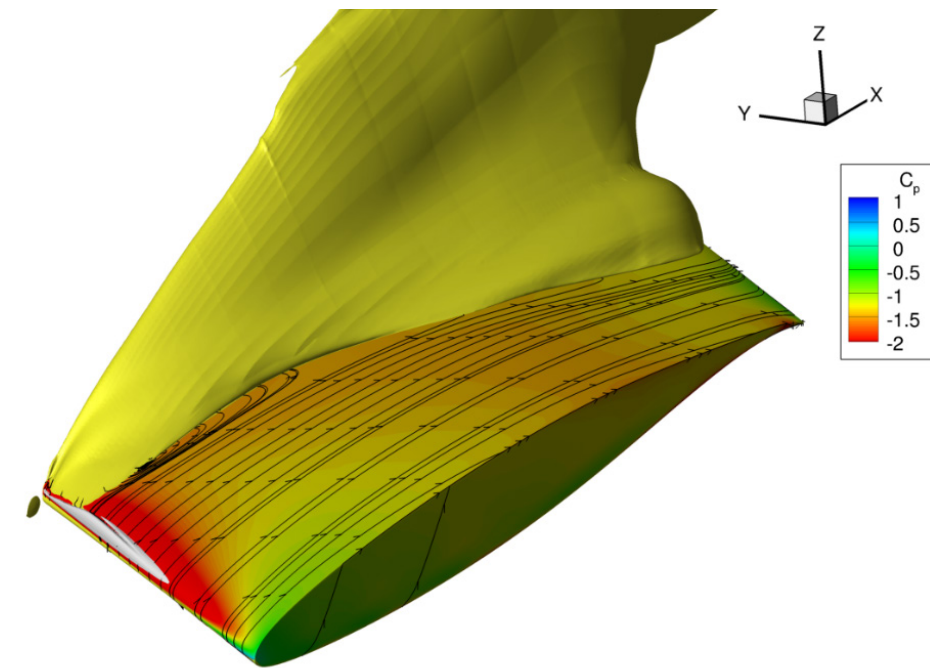


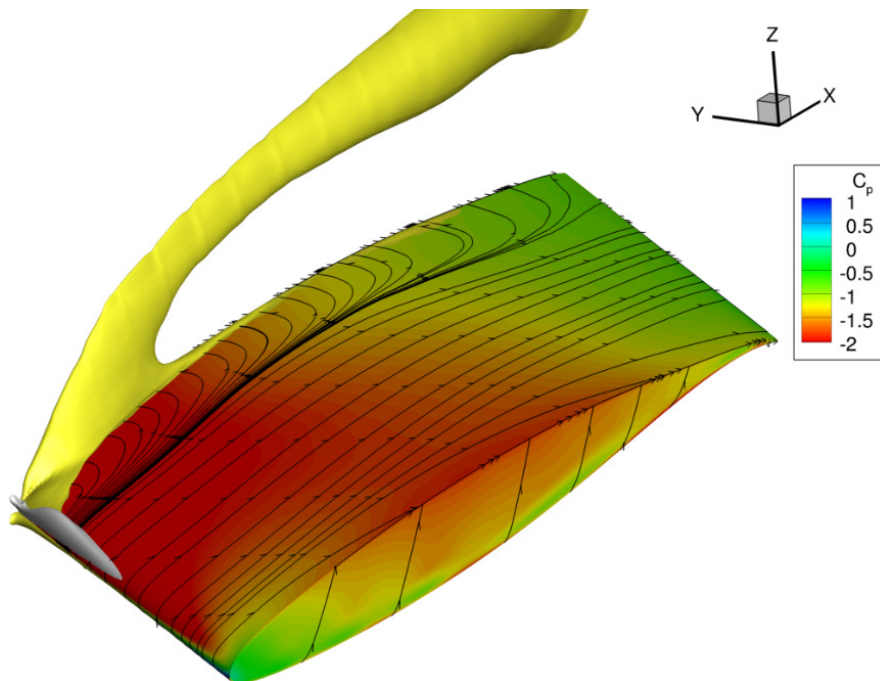
Figure 5.3.—Time-accurate calculations at high angle of attack.



$M_\infty = 0.41$
 $\alpha = 10^\circ$

Flow Field at iteration 30000

(a)



$M_\infty = 0.41$
 $\alpha = 10^\circ$

Averaged Flow Field at iteration 54000 ($t = 0.44$ sec)

(b)

Figure 5.4.—Effect of time-accuracy on full-scale midspan model. (a) Snapshot of the flow field at the end of the nontime accurate solution. (b) Snapshot of the flow field after 0.44 sec.

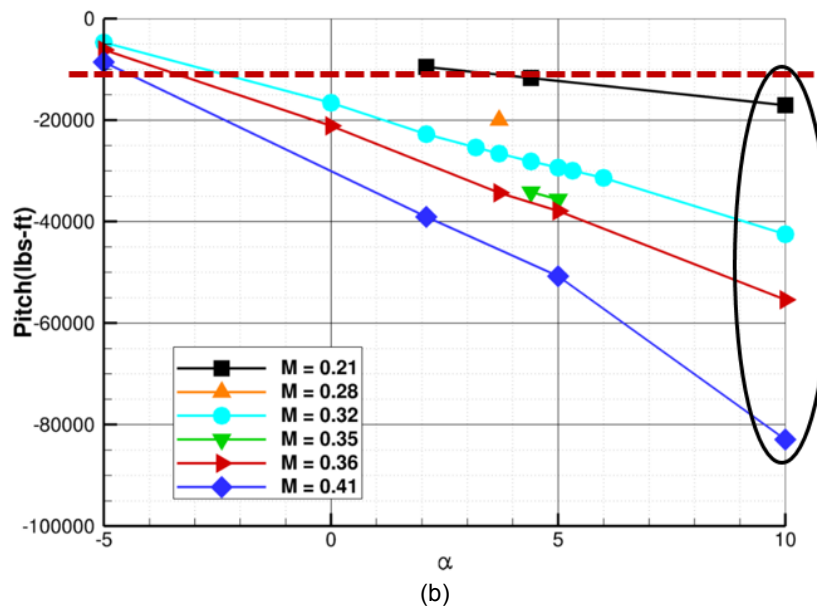
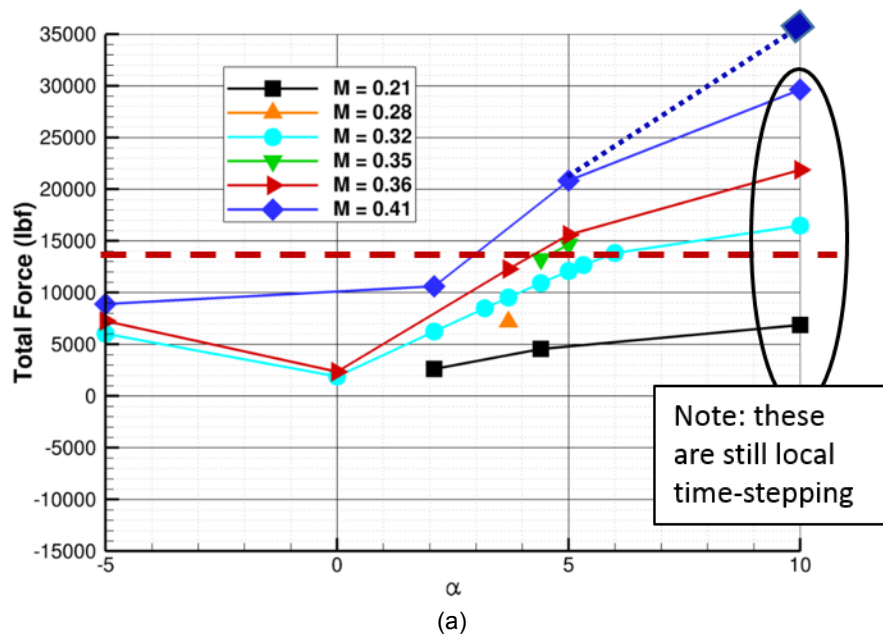


Figure 5.5.—Forces and moments on the full-scale model. (a) Turntable maximum load = 13,750 lbf. (b) Turntable maximum moment = $\pm 10,000$ ft-lbf.

Following the procedure described in Section 2.4 the stagnation line locations for the new full-scale model were extracted for the three nominal conditions (WB33, WB41, and WB52). The distance of the stagnation line location from the model highlight (s) as a function of span (η) is plotted in Figure 5.6 with positive values on the lower surface. The distance s , measured at midspan of the full-scale model ($\eta = 50$ percent) is compared with the corresponding distance to the stagnation line location for the CRM65 wing at span station $\eta = 64$ percent. The discrepancies, of more than 0.5 in., can be attributed to the effects of the tunnel walls and tunnel blockage on the flow, the model planform (no taper), among others. Matching the stagnation line location of the model with the CRM65 requires an increase in the model angle of attack. An aerodynamic calibration was performed and the results are shown in Figure 5.7, where the distance s as a function of model angle of attack is presented. The horizontal dashed lines represent the distance to the stagnation line of the CRM65 model at these nominal cases. The intersection points of these lines with the corresponding s - α curves are the model's new angles of attack that will match the CRM65 distances. A new set of flow fields using the updated angles was computed, the distances to the stagnation line location were extracted, and these are presented in Figure 5.8 where the original and the new distances are plotted as a function of wing span. It is apparent that the locations of the stagnation line for the full-scale model computed with the new angles match very well the CRM65 locations. This increase in angle of attack (between 0.77° to 1.09°) is associated with an increase in loads, but these new loads are still within the limits shown in Figure 5.5.

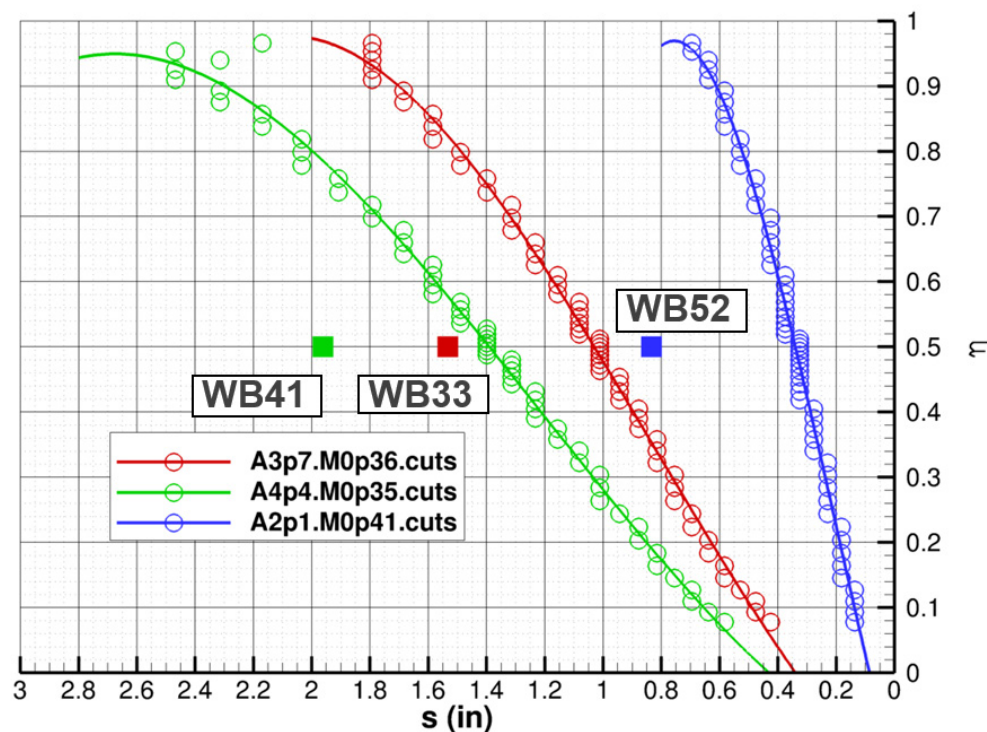


Figure 5.6.—Stagnation line distance from highlight for full-scale model.

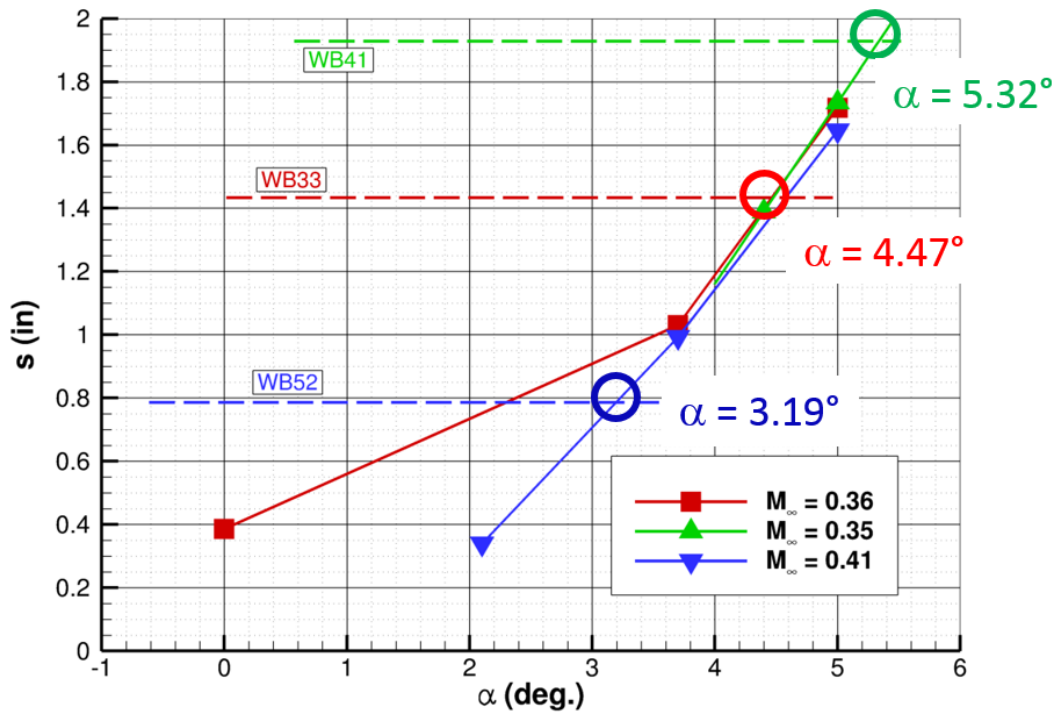


Figure 5.7.—Stagnation line location as function of angle of attack.

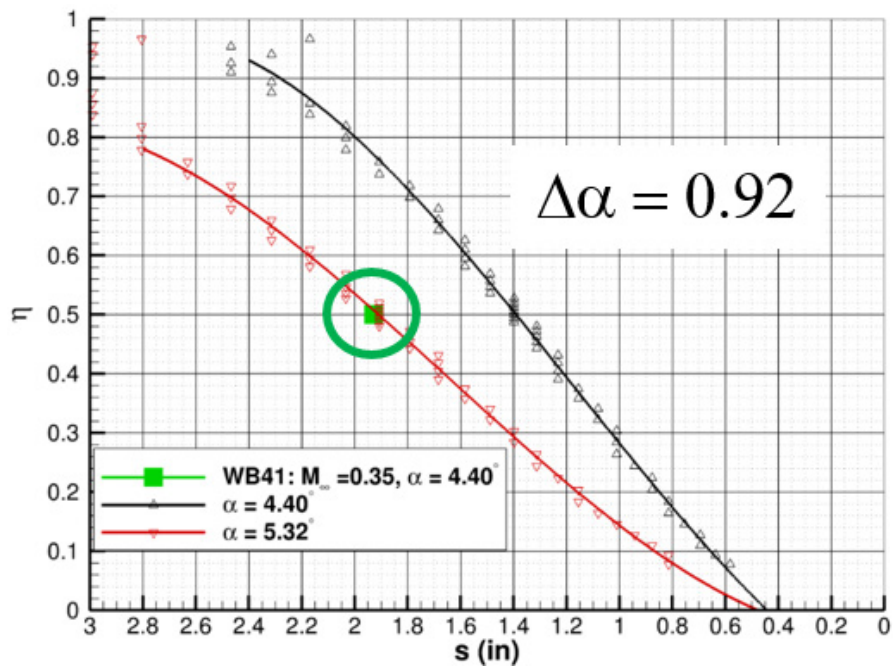
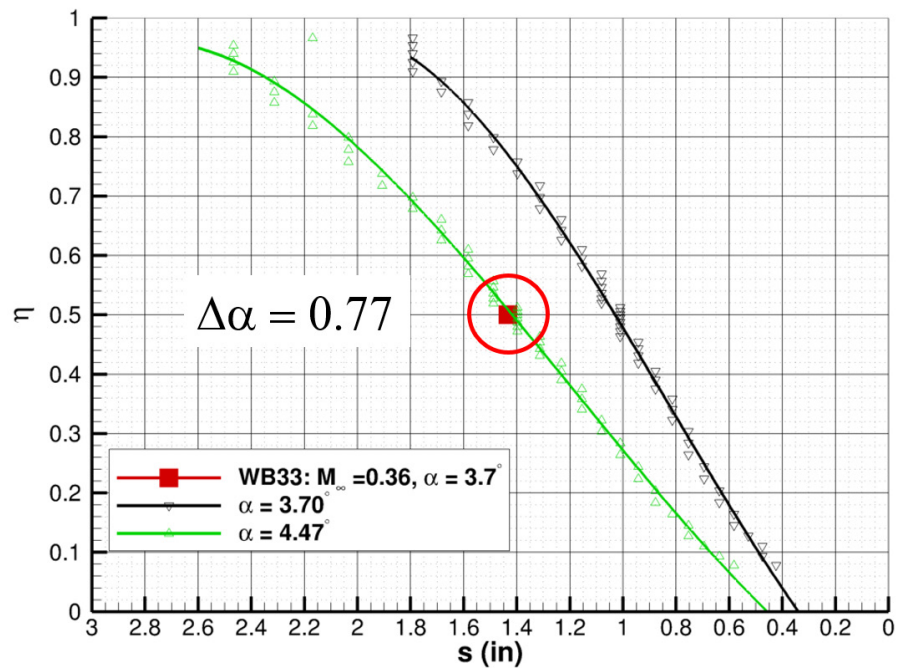
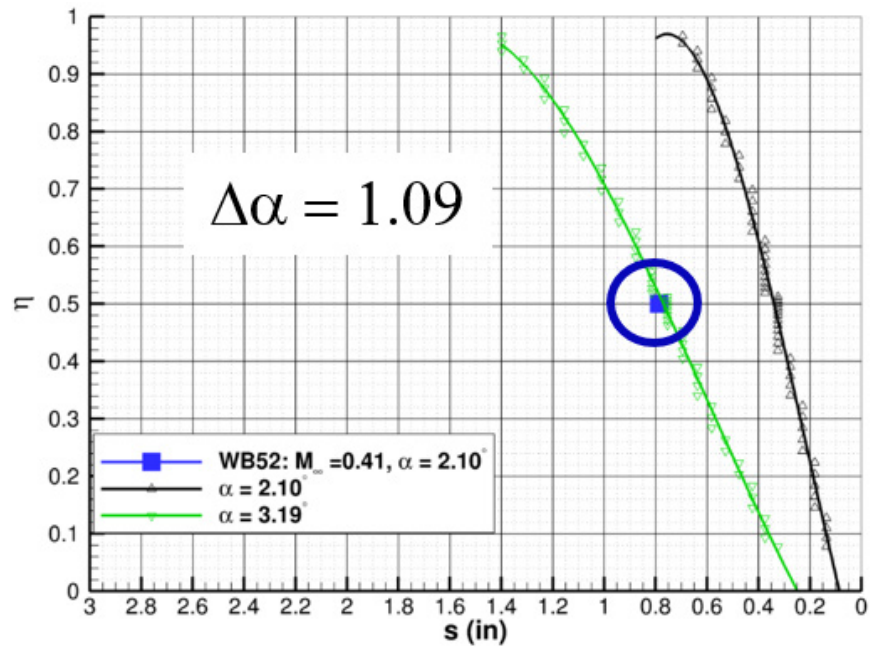


Figure 5.8.—Aerodynamic calibration of stagnation line location.



Reference Case	Mach Number	CRM65 WB Angle of Attack (deg.)	Full-Scale Model Angle of Attack (deg.)
WB33	0.36	3.7	4.47
WB41	0.35	4.4	5.32
WB52	0.41	2.1	3.19

Figure 5.8.—Concluded.

5.3 Flap Design for Full-Scale Model

While it has been demonstrated in Section 5.2 that the location of the stagnation line of the full-scale model can be made to match that of the CRM65 by adjusting the model angle of attack, it is often desirable to keep the original angle of attack of the CRM65 and use another mechanism to move the stagnation line to the desired location. The hybrid model was designed with a slotted flap to manipulate the stagnation line location while the model angle of attack was fixed. The full-scale model can be designed in a similar manner by adding a flap at the trailing edge. The most appropriate flap for this model would be a simple-hinge type because of its simplicity and its ability to keep the original cruise geometry of the model when retracted. Two sets of simple-hinge flap models are presented in Figure 5.9, F30, and F20. For the F30 model, a hinge-line was set at 70 percent x/c and the aft section of the model was deflected about that line down to 20° in 5° increments. The F20 model has a hinge-line at 80 percent x/c and the flap was deflected down to 30° in 10° increments.

To allow for a quick evaluation of the flap performance, a wall-to-wall grid topology was set up for each of the flap deflections and a set of CFD runs were performed. In this grid topology, gaps between the model and the tunnel walls (floor and ceiling) are ignored and the model spans the entire tunnel. This is in contrast to the “capped” topology used in Section 3.0, where the gaps between the tunnel floor and ceiling and the model were modeled by capping the edges of the model and leaving a gap between it and the tunnel walls. Past experience with similar models has shown that the major characteristics of the flow field can be modeled this way to reduce computation cost and time.

The effect of the flap deflection on the lift coefficient is shown in Figure 5.10. C_L - α curves for the two flap models as well as for the original un-deflected model (described in Section 5.2) are presented; the $\delta = 0^\circ$ correspond to the new wall-to-wall model with no flap deflection. It is apparent that the effect of the flap is to increase the lift for a given α , relative to the un-deflected model. Note that the new un-deflected model has a lower C_L relative to the original full-scale model at the angles of attack computed, likely due to the different grid topology. However, the general behavior is comparable, which justified the use of the simplified topology. It is also apparent that the larger flap (F30) is more efficient in lift production than the smaller flap (F20); it produces the same lift at a lower flap deflection for the same angle of attack.

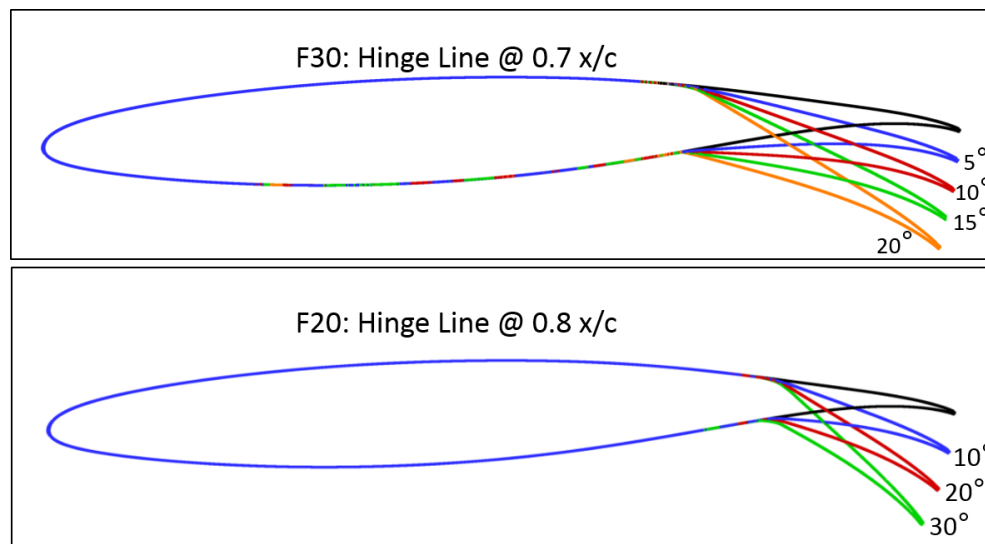


Figure 5.9.—Simple-hinge flap models.

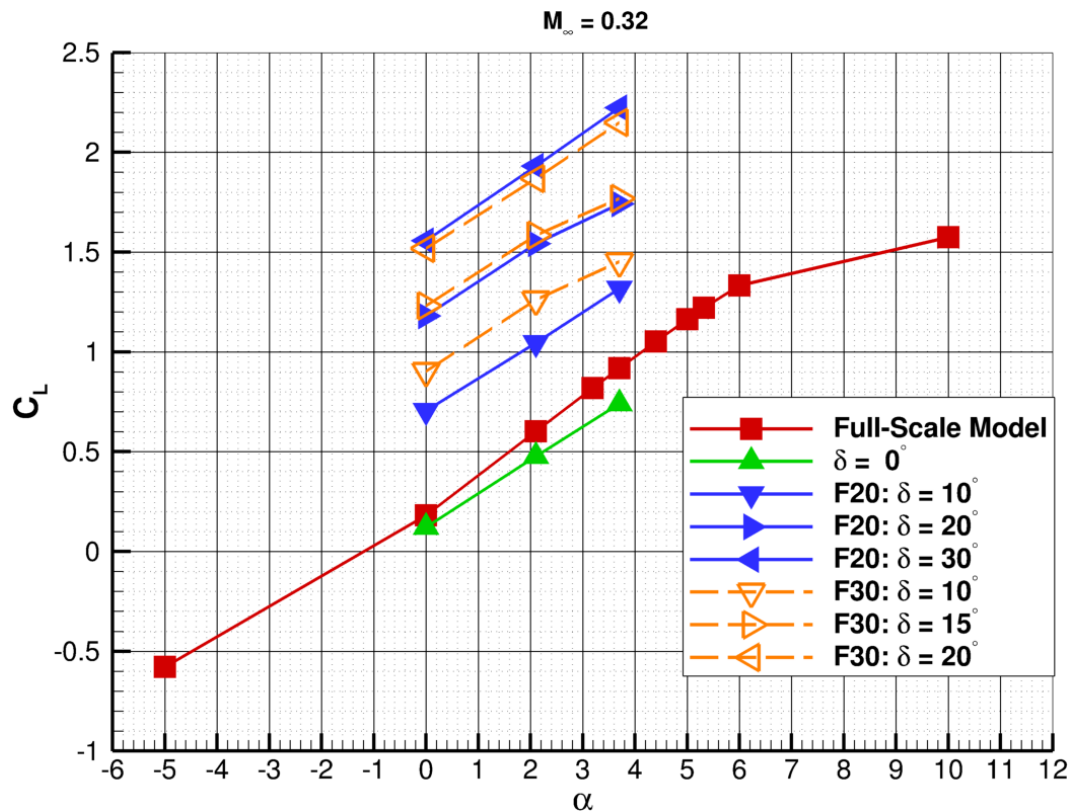


Figure 5.10.—Effect of flap size and deflection on model lift.

The effects of flap size and deflection on the stagnation line location is presented in Figure 5.11, where the distance from the model highlight to the stagnation line (s) as function of flap deflection (δ) is plotted for three angles of attack. The solid lines represent the smaller flap (F20) while the dashed lines represent the larger flap (F30). The effectiveness of the flap in controlling the stagnation line location can be measured by the slope of s - δ curves. It is apparent that the slopes of the curves for F30 flap, at all angles of attack presented, are steeper than that of the F20 flap. This means that for achieving the same stagnation line location, a F30 flap will require a smaller flap deflection angle. The benefits of lower flap deflection include lower drag, lower susceptibility to flow separation at the hinge line and reduced tunnel blockage. On the other hand it might create higher hinge moments that will require a stronger and heavier actuation system.

Following these observations, a new full-scale model was designed based of the F30 model. A trailing edge flap, conforming to the aft 30 percent of the full-scale un-deflected model was created with a hinge line at $0.7 x/c$. The flap was trimmed at the edges (floor and ceiling) to allow for a range of deflection from -5° to 30° without interfering with the tunnel walls. The trimmed flap was deflected to four positions ($\delta = 5^\circ, 10^\circ, 15^\circ$, and 20°) and the gap between the main element and the flap was sealed. The grid topology and setup of the model in the tunnel test section for the CFD calculation was similar to the one described in Section 5.2.

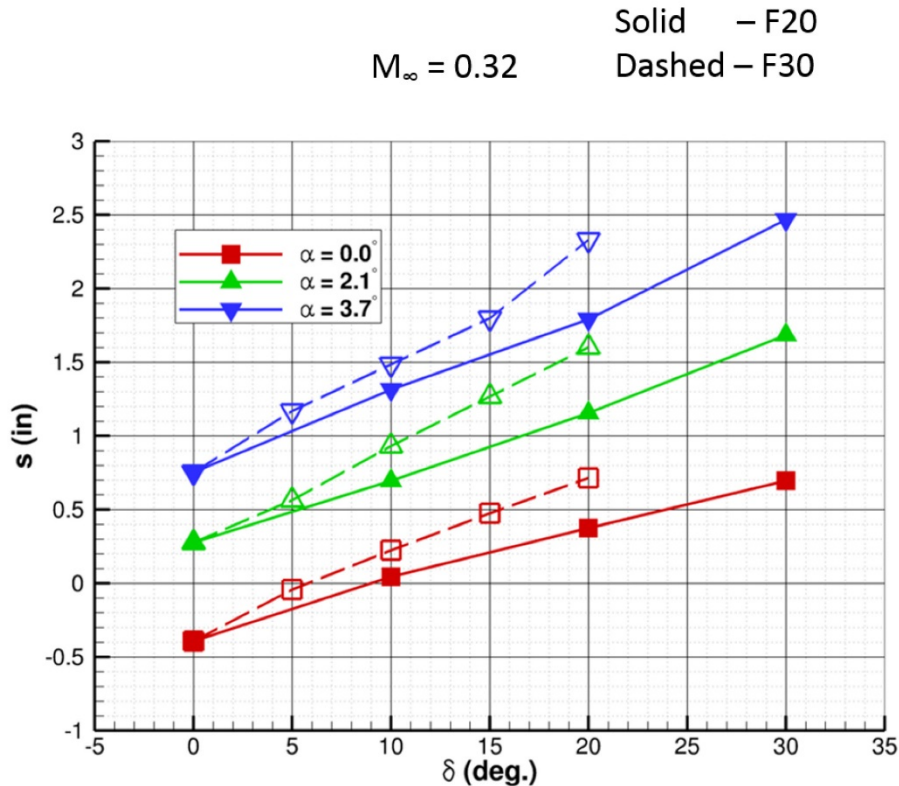


Figure 5.11.—Flap effectiveness.

5.4 Model Installation and CFD Analysis of the Simple-Hinge Flap Model

Based on the results presented in Figure 5.5 and Figure 5.10 it was clear that there is need for a method to reduce the loads and moments on the model in order to satisfy the structural limits of the turntable on which the model is to be mounted. The low height-to-chord ratio (H/C) for the full-scale model in the IRT (≈ 0.7) causes a significant acceleration of the flow over the upper surface of the model, suction side, resulting in increased loads. On the other hand, the flow of the lower surface, pressure side, is not affected by the low H/C and flow is more benign. Hence, one possible way to artificially increase H/C while preserving the model size is to move the model away from the upper wall and closer to the lower wall. Exploring this assumption, a series of CFD calculations were performed where the full scale model was moved toward and away from walls of the tunnel. Note that in the IRT the model is mounted vertically, so it is effectively being moved between the two side-walls of the tunnel, while in the CFD calculation the model movement is referred to as “up” and “down”. This series of cases were run at $M_\infty = 0.32$ and at a range of angles of attack.

The effects of the model position relative to the wall (“effective” H/C) are presented in Figure 5.12. Contours of pressure coefficients on a cut at the center of the model ($y = 36$) are shown at $\alpha = 3.7^\circ$ and four different locations on the model in the tunnel. The effect of model translation is an increase in the suction and consequently the loads as the model moves closer to the upper tunnel wall ($\Delta z = 10$ in.) and a reduction in suction and loads as it moves away from the upper wall ($\Delta z = -10$ in., $\Delta z = -15$ in.). Moving the model 15 in. down is effectively equivalent to an increase in the test section height-to-chord ratio by almost 30 percent.

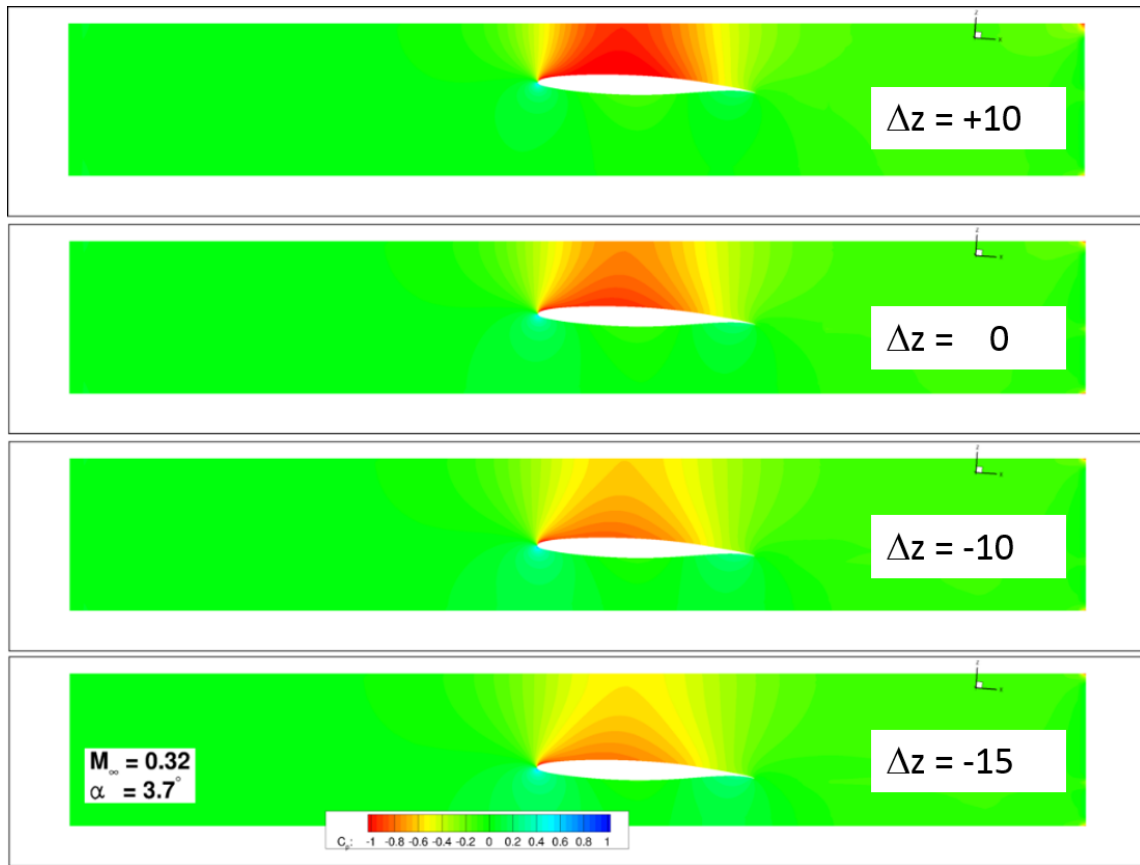


Figure 5.12.—Effects of model location on flow field.

The loads on the model as a function of the distance from the wall are presented in Figure 5.13. The reduction in loads is apparent for each of the angles of attack computed. The average reduction in load is 500 lbs for $\Delta z = -10$ in. and 750 lbs for $\Delta z = -15$ in.

The effect of the model translation on the stagnation line location is presented in Figure 5.14 and Figure 5.15. Contours of pressure coefficient on a cut through the center of the model for the four locations of the model relative to the tunnel walls are presented in Figure 5.14, focusing on the location of the maximum pressure near the leading edge. It is clear that while the levels of maximum C_p are different for each case, the change in its location is relatively small. (Note the center of the blue contour relative to the black vertical line). The more accurate effect of the model translation on the streamwise wrap distance from the model highlight (s) is presented in Figure 5.15. As the model moves away from the top wall the wrap distance increases, at increased rate as the angle of attack increases; the maximum change in the distance s for $\alpha = 3.7^\circ$ is 0.1692 in. and 0.2976 in. for $\alpha = 5.0^\circ$.

The model translation has an added effect on the loads on the turntable for a given stagnation line distance as described in Figure 5.16. In that figure the solid lines present the model lift coefficient (C_L) as function of stagnation line distance (s) for a given angle of attack (α) while the dashed line represent the $C_L - \alpha$ curves for a given model locations. For example, stagnation distance of 1 in. can be achieved at $\alpha = 3.7^\circ$ when the model is set at $z = 0$ (with $C_L = 0.92$) or at a lower angle of attack when the model is moved down by $\Delta z = -15$ in. (with $C_L = 0.80$). This reduction in C_L is equivalent to 1230 lbs reduction in force on the turntable.

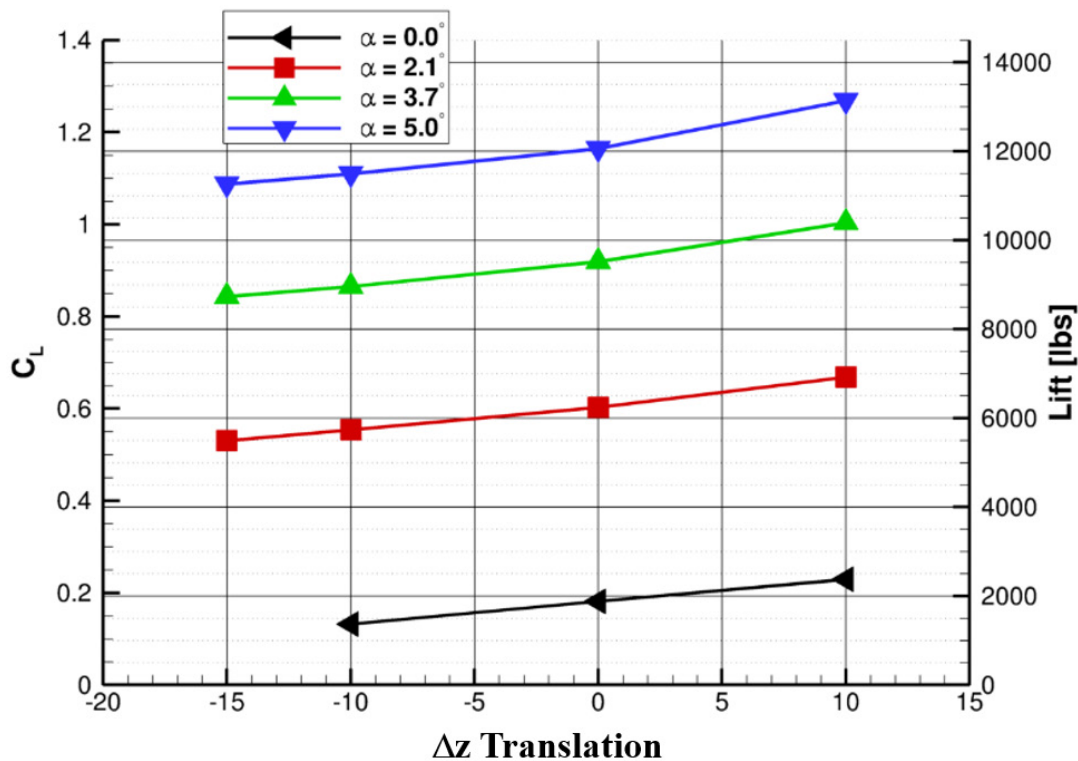


Figure 5.13.—Effects of model location on turntable loads and moments.

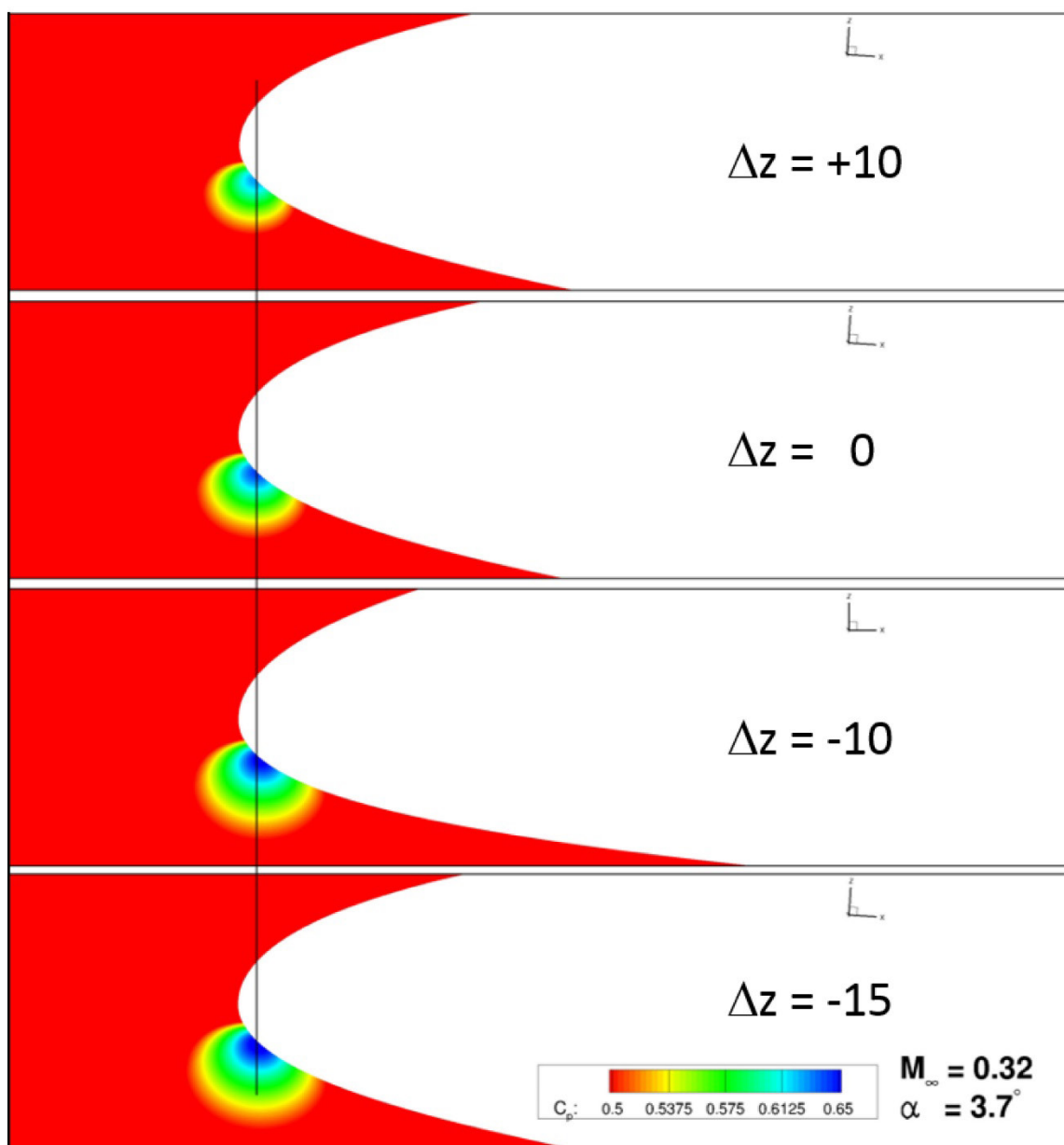


Figure 5.14.—Effects of model position on maximum pressure location.

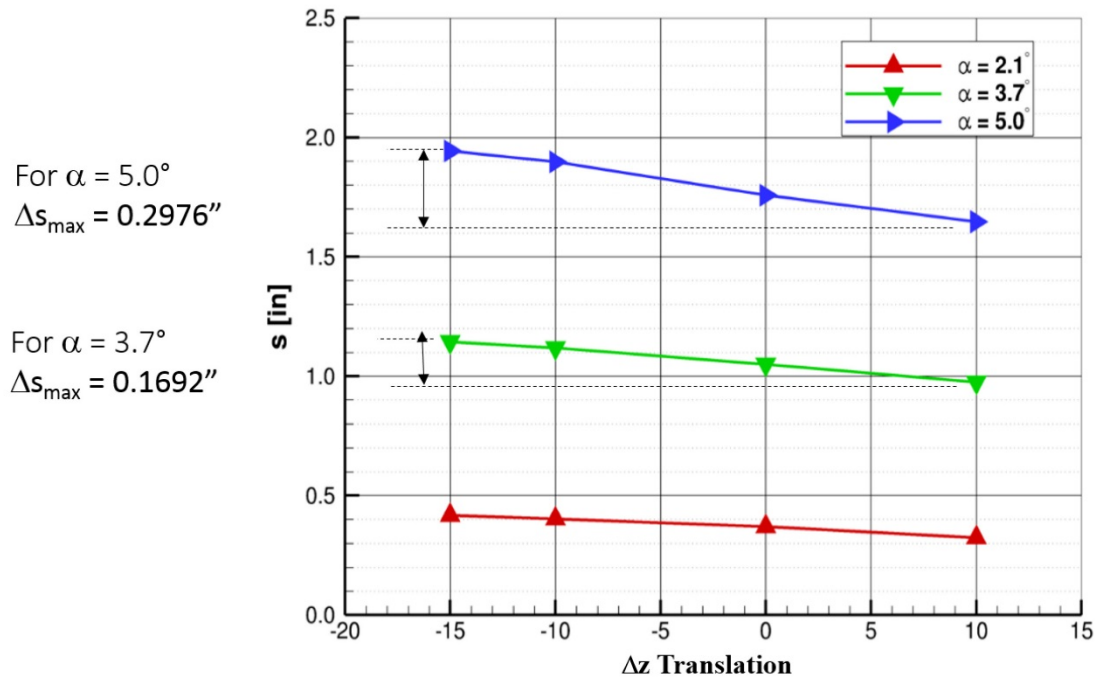


Figure 5.15.—Effects of model position on streamwise wrap distance from highlight.

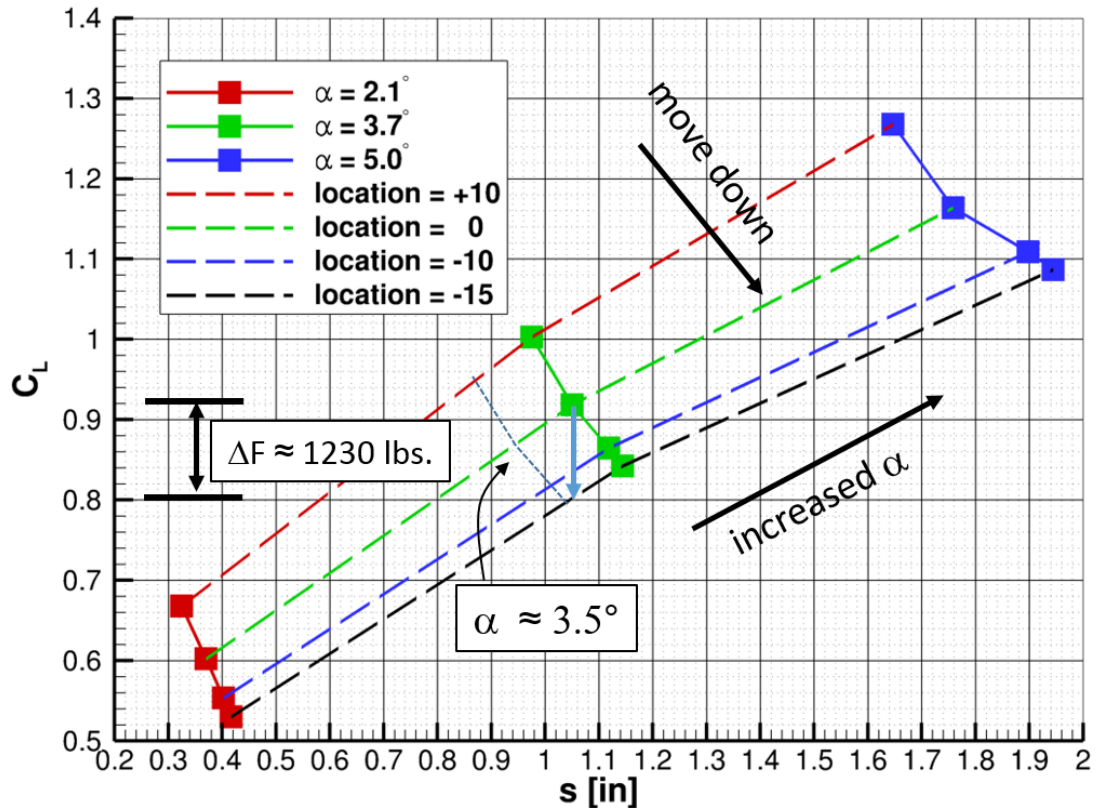


Figure 5.16.—Relations between model location and loads reduction.

Translating the model away from the wall reduced the loads and had an insignificant effect on the pitching moment. Since the original installation of the model matched the location of the MS model (Section 5.1) and the chord of the model is much longer, a large negative pitching moment is produced. To alleviate this negative pitching moment an upstream translation of the model is required. The computed pitching moment as function of angle of attack for several model locations are presented in Figure 5.17. In this set of CFD calculations, the model was translated 15 in. “away” from the upper wall ($\Delta z = -15$ in.) and moved upstream up to 40 in. from its original location. The effect of translation of the model upstream is to rotate the $C_M - \alpha$ curve in such a way that once the model moved at least 30 in. upstream the pitching moments are in the acceptable range for the entire α sweep. It is notable that for a $\Delta x = -40$ in. translation the leading edge of the model is located at $x = -102$ in. which is comparable to the location of the leading edge of the IB model, which has a similar size chord.

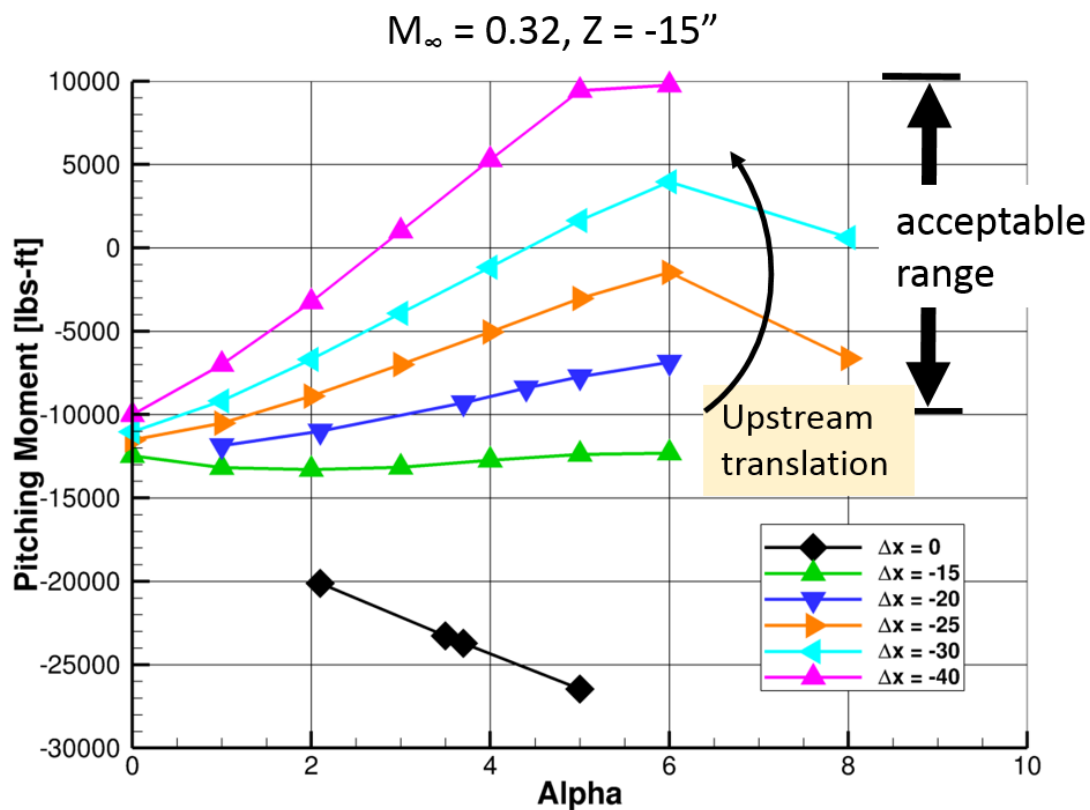
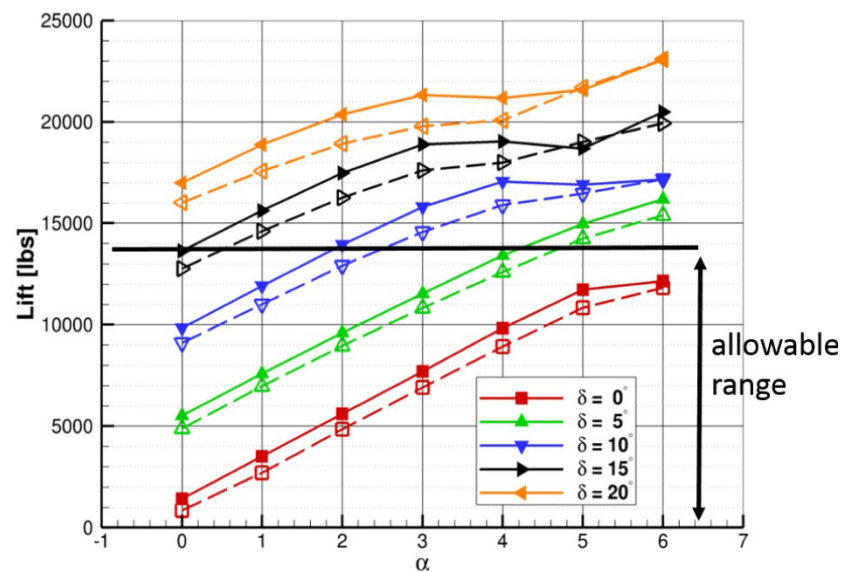


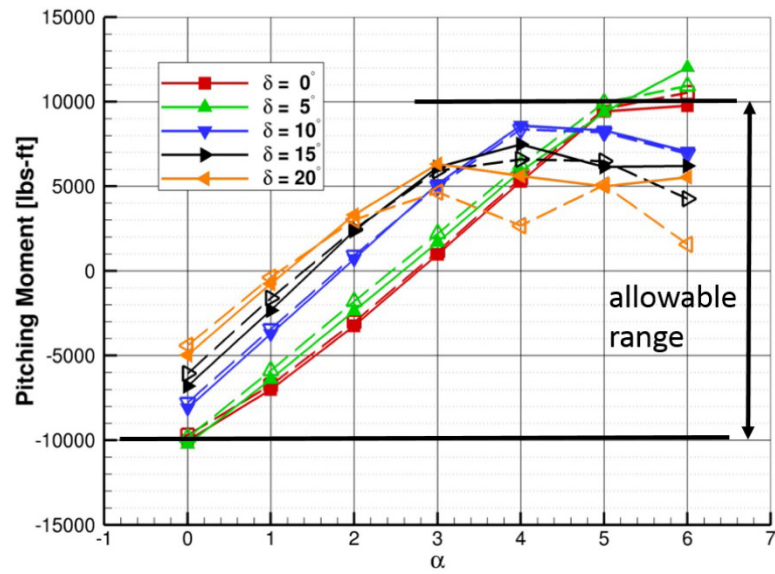
Figure 5.17.—Effect of model upstream location on pitching moment.

A complete set of CFD calculations for the full-scale, simple-hinge flap model was performed in order to create a database that can be used for aerodynamic calibration and model structural design. The freestream Mach number was set at 0.32, and simulations at a range of angles of attack and flap deflections were performed. In addition, the model was installed at two locations; the optimal location ($\Delta x = -40$ in., $\Delta z = -15$ in.) and an alternative location ($\Delta x = -40$ in., $\Delta z = 0$ in.). The alternative location was chosen in case instrumentation installation requirements will prevent moving the model off the center of the turntable. The lift, pitching moment and wrap distance (s) as function of angle of attack and flap deflection are shown Figure 5.18, Figure 5.19, and Figure 5.20, respectively. While the pitching moments of the entire run envelope are within the allowable range, the turntable load constraints will limit the range of angle of attacks at the higher flap deflections. For example, at flap deflection $\delta = 10^\circ$, any angle of attack above 2° will generate loads about the turntable limits. Figure 5.20, which describes the wrap distance from the highlight to the stagnation line (s), includes the distance s for the CRM65 wing at the three nominal conditions (three horizontal lines in red, blue and green). The slanted black line represent the loads and moment limits on the turntable; everything above the line is outside the acceptable range. It is apparent that despite the above mentioned limitations, the new model has a range of angles of attacks and flap deflections that will match the stagnation line locations of the CRM65 wing, as represented by the intersection of the colored horizontal lines with the s - α curves.



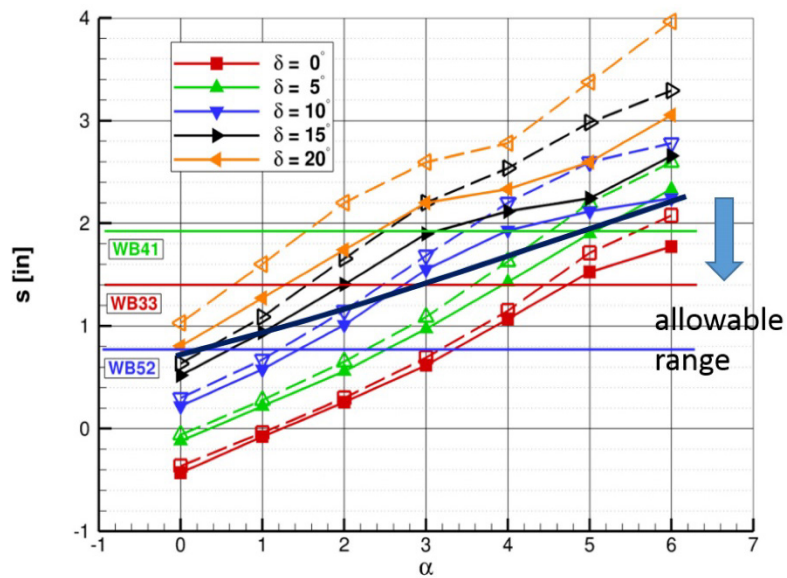
Z = 0 Solid line
Z = -15 Dashed line

Figure 5.18.—Lift on full-scale, simple-hinge flap model ($\Delta X = -40$ in., $M_\infty = 0.32$).



Z = 0 Solid line
 Z = -15 Dashed line

Figure 5.19.—Pitching moment on full-scale, simple-hinge flap model ($\Delta X = -40$ in., $M_\infty = 0.32$).



Z = 0 Solid line
 Z = -15 Dashed line

Figure 5.20.—Wrap distance to stagnation line on full-scale, simple-hinge flap model ($\Delta X = -40$ in., $M_\infty = 0.32$).

5.5 Aerodynamic Calibration of the Full-Scale Simple-Hinge Model

The database created in Section 5.4 can be used for the aerodynamic calibration process in which the appropriate flap deflection is chosen at the nominal angle of attack in order to match the required location of the stagnation line. An example of the calibration process is presented in Figure 5.21. For example, the nominal case WB33 was run at $\alpha = 3.7^\circ$ with the target distance s of 1.4 in. The intersection of the horizontal red line at $s = 1.4$ and the vertical dashed line at $\alpha = 3.7^\circ$ defines flap deflection angle δ . Since the intersection falls between two flap deflections it can be estimated to correspond to $\delta \approx 6.0^\circ$. Similarly, the new flap deflection for case WB44 and WB51 can be estimated as $\delta \approx 8.0^\circ$ and $\delta \approx 7.0^\circ$, respectively. A more systematic calibration can be done by extracting the distance s for each flap deflection at the given angle of attack and interpolate it to the required stagnation line distance. A summary of the wrap distances from the highlight to the stagnation line (s) for three angles of attack and five flap deflections are presented in Table 5.1. The interpolated flap deflection for the three nominal cases are presented in

Table 5.2. The data in both tables are for the two model positions described in Section 5.4 ($\Delta x = -40$ in., $\Delta z = 0$ in. and $\Delta x = -40$ in., $\Delta z = -15$ in.).

5.6 Updated Full-Scale Simple-Hinge Model

Upon running the initial LEWICE3D analysis, it was discovered that there were some significant discrepancies in geometry at the leading edge between the Full-Scale Simple-Hinge model, the Midspan Hybrid model and the WB CRM65 model. These discrepancies are as shown in Figure 5.22. To remedy this, a new Full-scale Simple-Hinge model was defined by grafting the leading edge of the MS hybrid model onto the full-scale model. This ensured that the leading edge geometries of the hybrid and full-scale models are identical, as shown in Figure 5.23. An aero-calibration process, as described in Section 5.5 was performed on the new model in order to find the appropriate flap deflection angle. The calibration was performed on one model position, $\Delta x = -40$ in., $\Delta z = 0$ in., (model at the turntable center) and the results are summarized in Table 5.3 and Table 5.4. Note that this aero-calibration was performed for the WB33 case only. The flow field computed using the new model and the updated flap deflections were used in the LEWICE3D calculation to be described next.

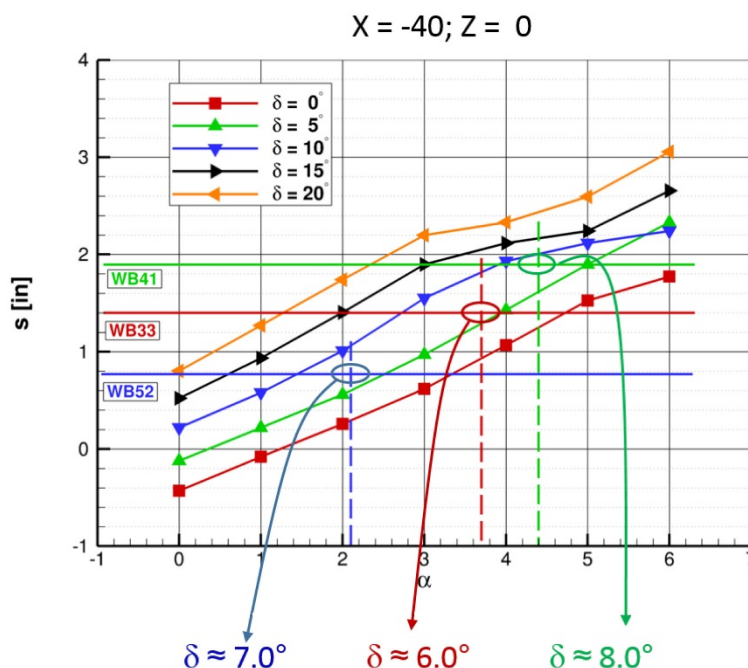


Figure 5.21.—Aerodynamic calibration of full-scale simple-hinge flap model.

TABLE 5.1.—STAGNATION LINE WRAP DISTANCE AS FUNCTION OF FLAP DEFLECTION

	$\Delta Z = 0$				$\Delta Z = -15$		
	s (in.)				s (in.)		
Flap deflection δ , degree	$\alpha = 2.1^\circ$	$\alpha = 3.7^\circ$	$\alpha = 4.4^\circ$	Flap deflection δ , degree	$\alpha = 2.1^\circ$	$\alpha = 3.7^\circ$	$\alpha = 4.4^\circ$
0	0.291	0.941	1.266	0	0.336	1.011	1.374
5	0.596	1.331	1.617	5	0.697	1.467	1.857
10	1.063	1.630	2.022	10	1.202	2.044	2.357
15	1.457	1.925	2.150	15	1.710	2.436	2.716
20	1.793	2.250	2.408	20	2.238	2.725	3.018

TABLE 5.2.—INTERPOLATED FLAP DEFLECTION FOR NOMINAL REFERENCE CASES

$\Delta Z = 0$				$\Delta Z = -15$		
AoA, degree	Target distances, in.	Flap deflection δ , degree		AoA, degree	Target distance, s, in.	Flap deflection δ , degree
2.1	0.786	7.030		2.1	0.786	5.811
3.7	1.433	6.097		3.7	1.433	4.354
4.4	1.928	6.946		4.4	1.928	5.370

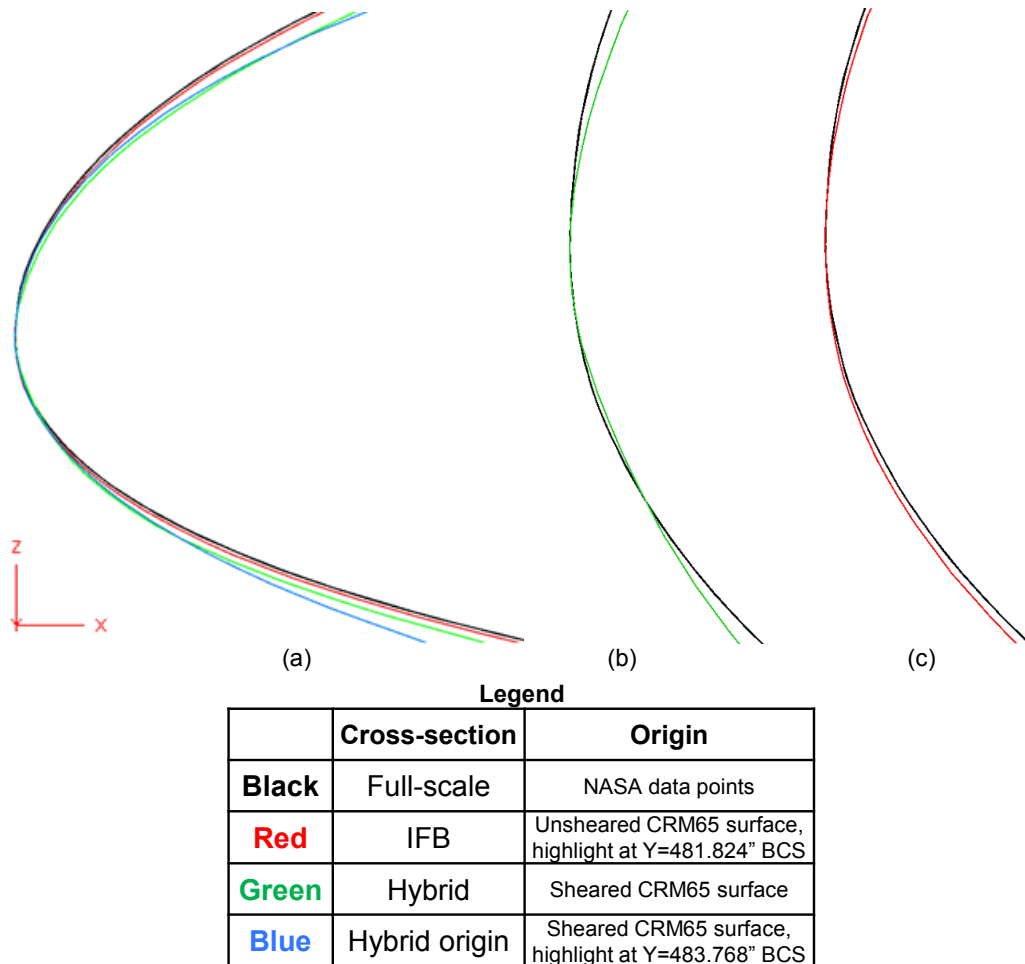


Figure 5.22.—Original leading edge geometry discrepancies on cuts normal to the leading edge.
 (a) Overall view of all shapes. (b) Close-up view of hybrid to full-scale comparison showing significant mismatch. (c) Close-up view of IFB to full-scale comparison.

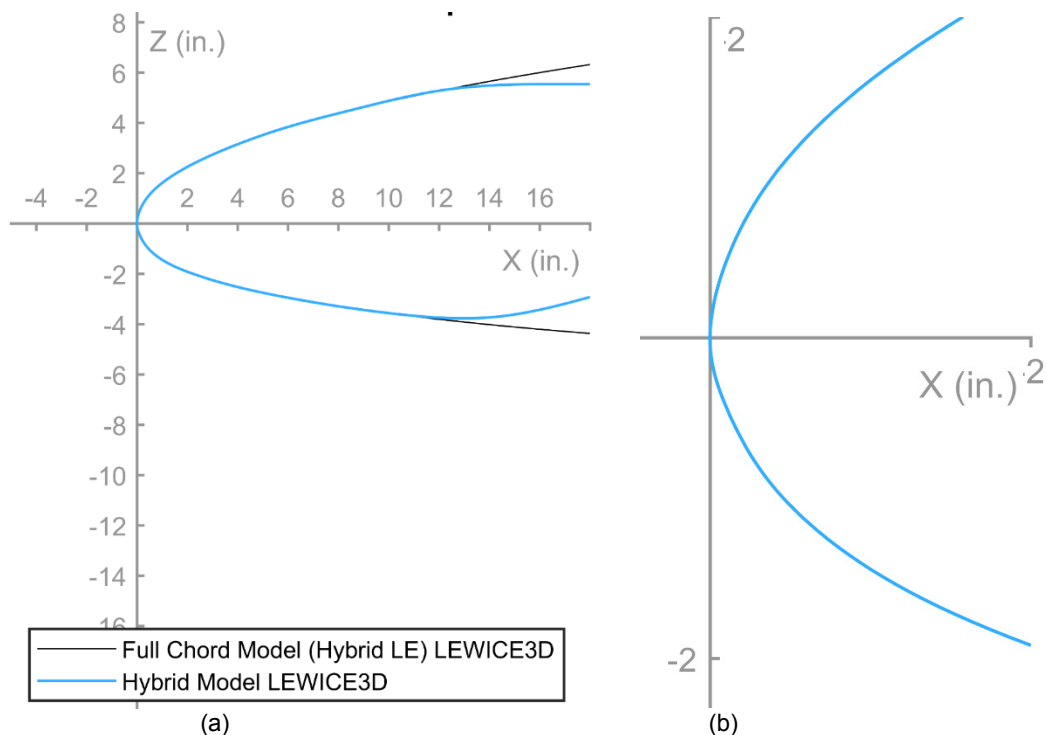


Figure 5.23.—Leading edge geometries remedied (normal cuts to leading edge). (a) Overall view of all shapes. (b) Close-up view of hybrid to full-scale comparison showing match.

TABLE 5.3.—STAGNATION LINE WRAP DISTANCE AS FUNCTION OF FLAP DEFLECTION

Flap deflection δ , degree	$\Delta Z = 0, \alpha = 3.7^\circ$	
	s , in.	
	$M = 0.20$	$M = 0.32$
3.5	1.398	1.339
4.5	1.517	1.428
5.5	1.592	1.517

TABLE 5.4.—INTERPOLATED FLAP DEFLECTION FOR NOMINAL REFERENCE CASES FOR UPDATED MODEL

Case	AoA α , degree	Target distance s , in.	Flap deflection δ , degree	
-----	-----	-----	$M = 0.20$	$M = 0.32$
WB33	3.7°	1.4	3.51	4.19

6.0 Ice Accretion Analysis of Full-Scale Midspan Model

The next section describes the ice accretion analysis performed on the full-scale simple-hinge flap model described in Sections 5.3 and 5.4. The flow fields used for the analysis are the ones computed on the model with the updated leading edge described in Section 5.6. The icing conditions were set up by mutual agreement between the NASA PI and the contractor. These conditions represent a departure from App. C envelope used in icing certification and should not be used for certification of commercial aircraft, except for the WB33 Direct App. C condition. The setup for the icing calculations followed by the resulting ice shapes for the full-scale Midspan IRT test model will be described next.

6.1 LEWICE3D Setup

The IRT Cloud Calibration 7-bin drop distribution (discussed in Section 4.1) with the appropriate MVD value was used for the full-scale Midspan model. The ice density for all cases was 450 kg/m^3 .

The analysis utilized the Boeing version of LEWICE3D and supporting scripts, “LEWICE3D Package 3.2,” which incorporate various best practices developed for icing modeling within the Boeing Company.

6.2 Results

LEWICE3D was run on the full-scale Midspan model configuration for the following set of conditions shown in Table 6.1. The stagnation line was set to a nominal position of $s = 1.4 \text{ in.}$, which required a flap angle of 3.5 degrees for the $M = 0.20$ case.

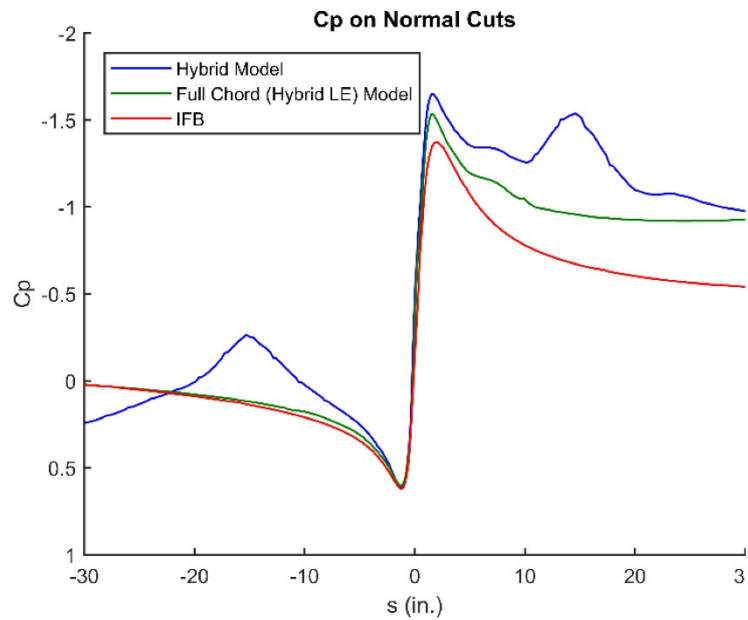
Previous studies of hybrid icing models looked at the effects of the Scale Factor (SF), defined as the ratio of the full-scale chord to the hybrid model chord, on the flow field and icing characteristics. For example, it was found that as SF increases (hybrid model chord decreases), peak suction increases (C_p more negative), collection efficiency (β) increases, and ice tends to extend farther along the upper surface. For more details see Reference 9.

When comparing the ice shapes between the WB CRM65 case (IFB), the MS hybrid model and the new full-chord, simple-hinge model it is worth noting that the SF of MS hybrid model is around 2.9, based on the main element only and SF of 2, based on the entire model (main and flap). The SF for the full-chord, simple-hinge model is 1.

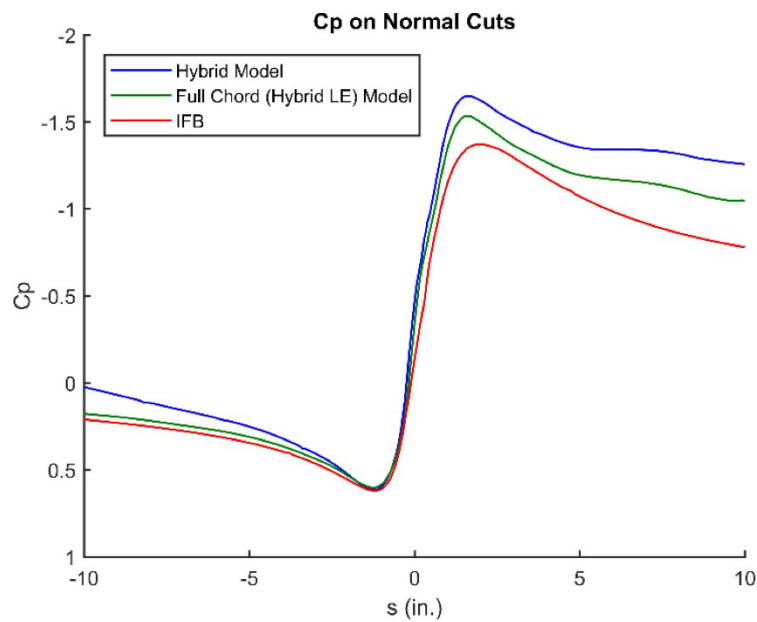
A comparison of pressure distribution between the hybrid model, full-chord model, and IFB at the midspan location is shown in Figure 6.1. Note that in this, and the following figures, positive s is along the upper surface. The maximum C_p location is the same for all cases, as by design. The hybrid model has a slightly higher suction peak than the full-chord model, as expected, based on the Scale Factor. The full-chord model and IFB curves match well because they are similar in overall shape, except on the upper surface where the wind-tunnel wall effects are dominant. Other differences of the hybrid model curve compared to the others are due to the hybrid model closure curvature.

TABLE 6.1.—ICING CONDITIONS FOR FULL-SCALE MIDSPAN MODEL IN THE IRT TEST SECTION

Ice type	AoA, degree	Speed, knots	Ps, psia	Ts, °C	MVD, μm	LWC, g/m^3	Spray time, min.	Mach	Alt., feet
Venetian blind scallop	3.7	129	13.97	-6.2	25.0	1.00	29.0	0.20	1379
Max scallop	3.7	129	13.74	-8.6	25.0	1.00	29.0	0.20	1828
Small gap scallop	3.7	130	13.81	-11.0	25.0	1.00	29.0	0.21	1689
Incomplete scallop	3.7	130	14.03	-13.6	25.0	0.99	29.0	0.21	1262
Streamwise/rime	3.7	130	13.93	-20.3	25.0	0.60	23.0	0.21	1452
WB33 direct App. C	3.7	129	14.02	-5.4	27.6	0.91	45.0	0.20	1283



(a)



(b)

Figure 6.1.—Pressure distribution comparison between hybrid and full-scale models. (a) Overall view. (b) Close-up view of leading edge region. Note: $s = 0$ is defined at the highlight (clean airfoil point of minimum X).

Comparison of collection efficiency between the hybrid model, full-scale model, and IFB at the midspan location are shown in Figure 6.2 and Figure 6.3 for IRT MVD's of 25 and 27.6 μm , respectively. The insert in each figure is an expanded view around β_{max} . Table 6.2 displays the stagnation line location, maximum value of collection efficiency, and total water catch values (E_{mh}) for the curves shown in both figures. The stagnation line locations listed are slightly different from the CFD results in Section 5.6 because s was measured perpendicular to the leading edge and because LEWICE3D calculates slightly different C_p 's (and therefore stagnation location) from CFD solutions. Note that the IFB data shown is the same in both figures. The differences in collection efficiency between the hybrid model and the full-scale one follow the trend described above, where an increase in SF results in an increase in β_{max} . The difference in impingement limits and total water catch values are reasonable between the two and are likely due to the hybrid model lower surface cutoff and the hybrid model not having the full-scale thickness. The hybrid model matches IFB better than the full-chord model, which may potentially be due to the large amount of blockage in the IRT with the full-chord model installed.

Figure 6.4, Figure 6.5, Figure 6.6, Figure 6.7, Figure 6.8, and Figure 6.9 show comparisons between the LEWICE3D full-chord Midspan model (with the hybrid model leading edge), the LEWICE3D hybrid Midspan model, the LEWICE3D IFB case at the Midspan cut, and the MCCS shape scanned from the Midspan model in the IRT test. The LEWICE3D shapes match each other well overall with small differences in upper and lower surface impingement limits. Despite these differences, the hybrid and full-scale model ice shapes match IFB ice well considering the effects of the icing tunnel walls.

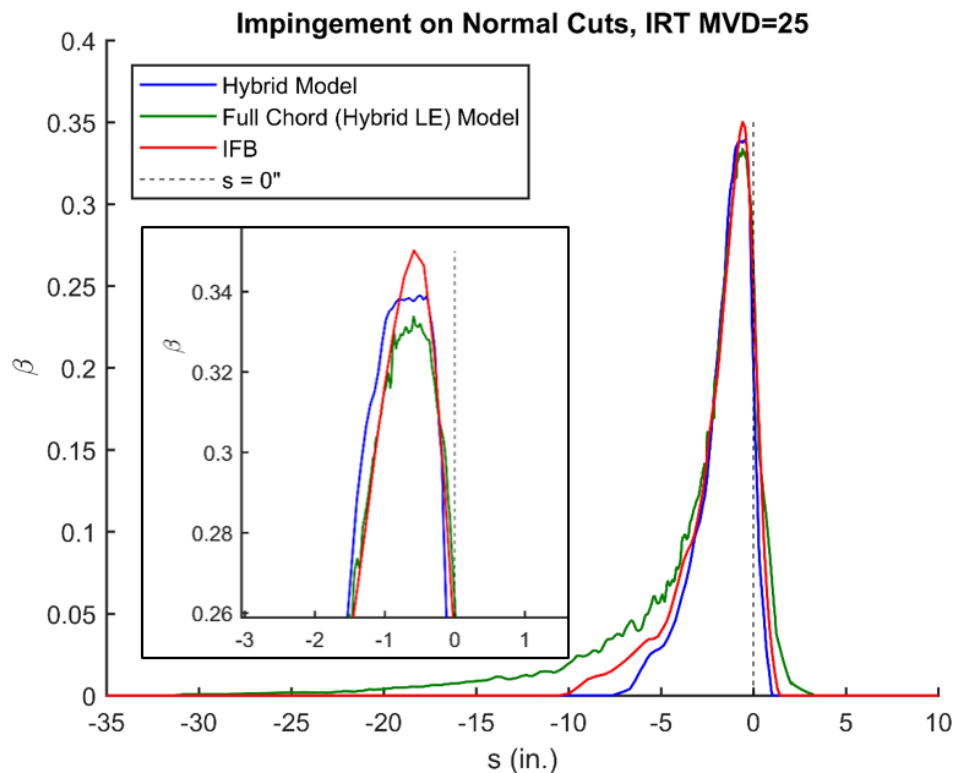


Figure 6.2.—Collection efficiency comparison of hybrid model, full-chord model, and IFB, with IRT MVD = 25 μm . Note: $s = 0$ is defined at the highlight (clean airfoil point of minimum X).

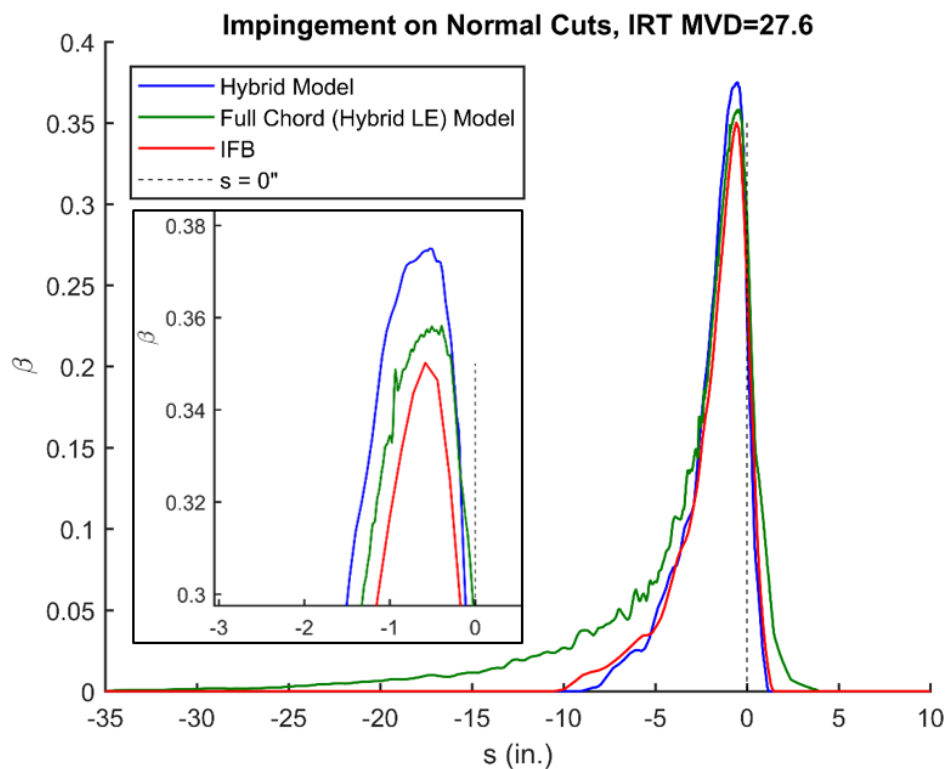


Figure 6.3.—Collection efficiency comparison of hybrid model, full-chord model, and IFB, with IRT MVD = 27.6 μm . Note: $s = 0$ is defined at the highlight (clean airfoil point of minimum X).

TABLE 6.2.—IMPINGEMENT COMPARISON OF THE HYBRID MODEL, FULL-CHORD MODEL, AND IFB

Geometry	Drop distance	MVD, μm	Sstagnation, in.	β_{max}	Em_h total	Em_h , upper surface
Hybrid model	IRT	25.0	-1.24	0.339	0.95	0.07
Full chord (Hybrid LE) model	IRT	25.0	-1.23	0.334	1.37	0.18
Hybrid model	IRT	27.6	-1.24	0.375	1.12	0.10
Full chord (Hybrid LE) model	IRT	27.6	-1.23	0.358	1.60	0.22
IFB	Langmuir D	20.0	-1.13	0.350	1.09	0.13

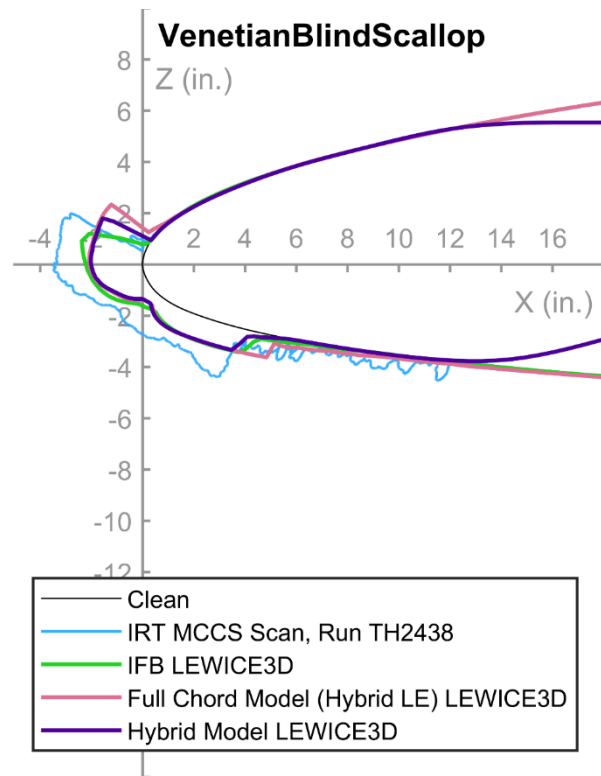


Figure 6.4.—Venetian blind scallop full chord model to IFB comparison.

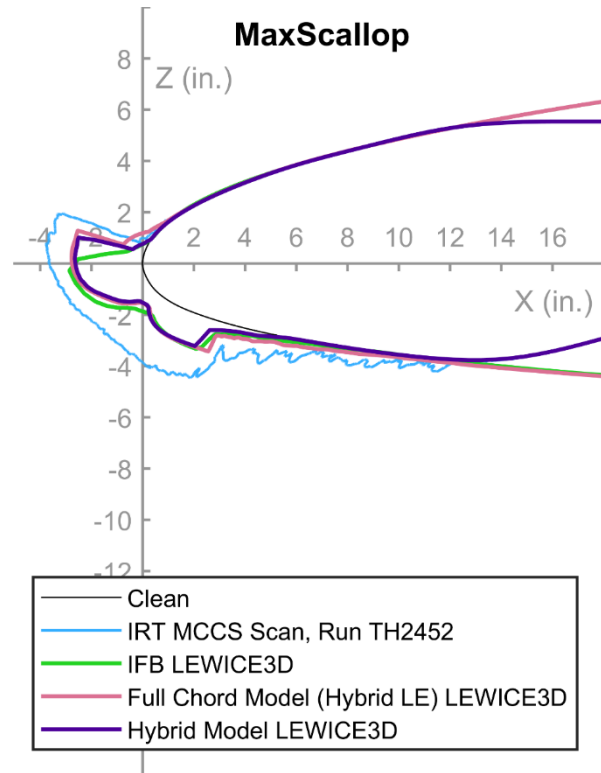


Figure 6.5.—Max scallop full chord model to IFB comparison.

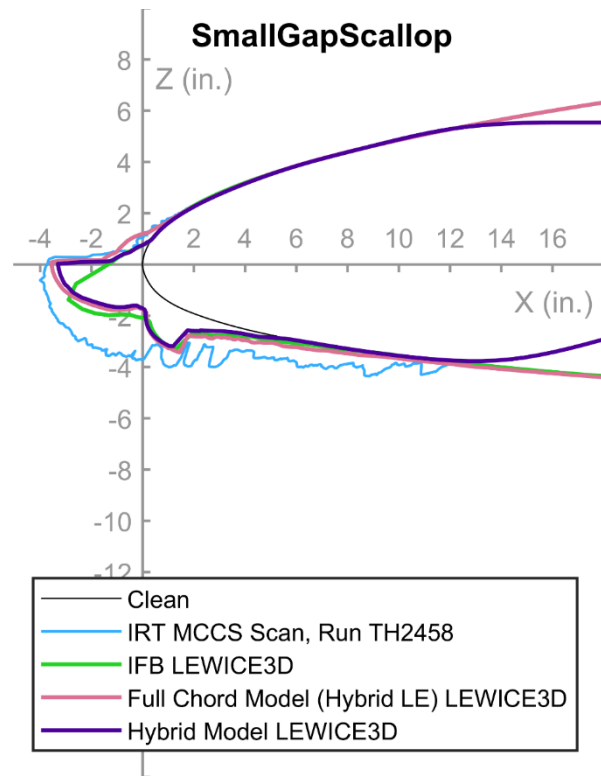


Figure 6.6.—Small gap scallop full chord model to IFB comparison.

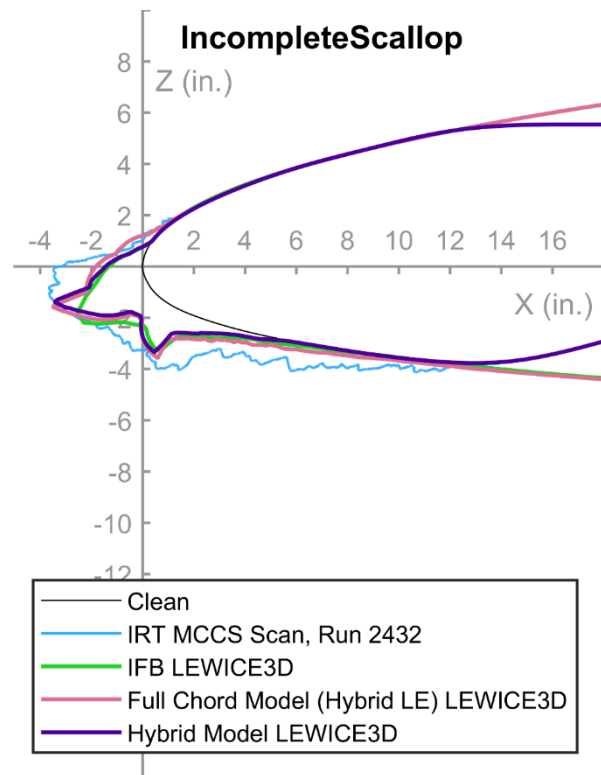


Figure 6.7.—Incomplete scallop full chord model to IFB comparison.

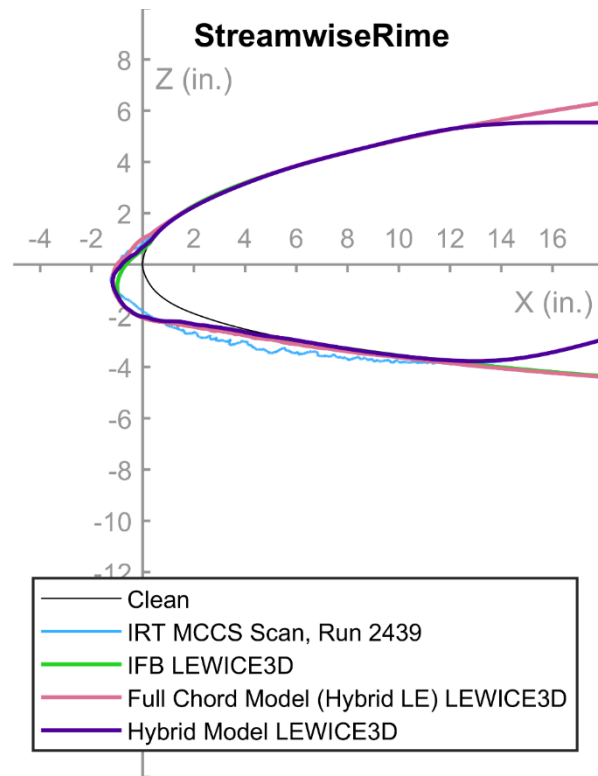


Figure 6.8.—Streamwise/rime full chord model to IFB comparison.

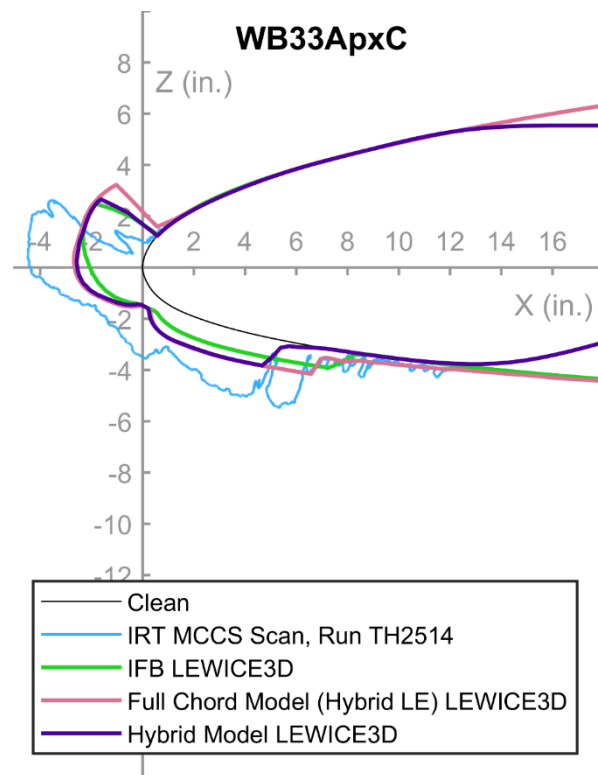


Figure 6.9.—WB33 direct App. C full chord model to IFB comparison.

7.0 Summary

This report describes the work done under NASA Contract NNL16AA044B Task Order NNC16TA90T. It included two distinct tasks. In the first task, the flow fields at the three nominal conditions were computed over the un-sheared CRM65 WB configuration in order to supplement the data created for the sheared wing during the previous phase, under contract NCC10BA05-NNC14TA3T. An extended set of icing conditions was selected and ice shapes were computed on the WB configuration. In addition, another set of flow fields and ice shapes were computed on the three IRT hybrid models and compared with the MCCS shapes measured in the IRT. The LEWICE3D computed ice shapes matched the relative aerodynamic impact of the MCCS shapes well overall even though the actual ice shapes are not identical. However, some improvements to the tool are needed to achieve better agreement in cases such as glaze ice at warm temperatures, beak ice, and rime ice.

The second task called for a design of a new full-chord model for the IRT. The full-chord model will help understand the differences in ice shapes between full CRM65 WB wing and the hybrid models used in icing testing. The new full-chord model was based on a section, normal to the leading edge, taken at 64 percent semispan; the location from which the Midspan IRT hybrid model was based on. A CFD-computed database was created in order to validate the usability of the model within the IRT turntable structural limits, while providing flow fields with stagnation lines at location comparable to the CRM65 WB model for the nominal conditions. It was found that by installing the new model such that its leading-edge on the floor is located at ~100 in. upstream from the turntable, these limits can be satisfied.

A requirement for a finer control of the stagnation line location led to the addition of a flap to the full-chord model. A simple hinge flap, with hinge line located at 70 percent chord, was chosen allowing for simple flap installation and preserving the ability for full-chord testing. A set of flow fields were computed on the new full-chord simple-hinge model and ice shapes computed by LEWICE3D were compared with the MS hybrid model and the CRM65 WB configuration. The ice shapes computed on the MS hybrid model and the full-scale model are very similar to each other when the stagnation line location is matched. These ice shapes compare well with the ones computed on the CRM65 WB configuration (IFB) where the slight differences can be attributed to the difference in flow field due to the presence of the wind tunnel walls.

8.0 Supporting Data

The data developed for this contract can be divided into three sets. The first set are the files needed to perform the 3D RANS-based CFD analysis, using OVERFLOW and the output files resulted from the simulations. These data are used as the inputs for the ice accretion calculations. The second set of data are the input files needed to set up LEWICE3D and the resulting ice shapes generated by it. The third set is the Microsoft Excel (Microsoft Corporation) spreadsheet created by the Ice Shape Comparison Exercise described in Section 4.4.

Each OVERFLOW run requires at a minimum the following files:

- *grid.in*: PLOT3D format, 3D, multi-zone, unformatted, double precision
- *XINTOUT*: a binary file generated by PEGASUS; includes the connectivity and interpolation information needed for the overset grid system
- *Mixsur.i*: an ASCII file used as input for **mixsur** which create composite surfaces on which forces and moments are computed. **mixsur** is executed before the OVERFLOW run creating a set of files used by OVERFLOW at run time
- *Overflow.inp*: an ASCII file used as input to OVERFLOW

At the end of the run OVERFLOW saves the final flow field solution in *q.save*; PLOT3D format, 3D, multi-zone, unformatted, double-precision file. These sets of files for each of the OVERFLOW runs in Tables 4.2, 4.3 and 6.1 will be transmitted to NASA PI.

The files needed for the LEWICE3D are *grid.in*, *q.save* and *mixsur.fmp* from the OVERFLOW runs and LEWICE3D fort.2 input files. LEWICE3D output files are the TECPLOT case visualization files and the fort.26 files that are converted into RMS files containing the ice shapes.

These files will be attached to the final report:

- Excel spreadsheets with input data
 - “IRT LEWICE3D Inputs - Task 2.1.3.xlsx”
- RMS Files
 - “4.2 IFB Ice Shape LEWICE3D .rms Files.zip”
 - “4.3 IRT Ice Shape LEWICE3D .rms Files.zip”
 - “6.2 MS Full-Scale Ice Shape LEWICE3D .rms Files.zip”
- TXT Files and Plot Images
 - “4.2 IFB Ice Shape MS Plots, XZ Plane.zip”
 - “4.3 IRT Ice Shape Plots, XZ Plane.zip”
 - “6.2 MS Full-Scale Ice Shape Plots, XZ Plane.zip”
- DAT Files
 - “4.2 IFB Ice Shape TECPLOT .dat Files.zip”
 - “4.3 IRT Ice Shape TECPLOT .dat Files.zip”
 - “6.2 MS Full-Scale Ice Shape TECPLOT .dat Files.zip”
- Ice Shape Comparison Exercise matrix described in Section 4.4
 - “Ice Shape Comparison - NASA Swept Wing v3.xlsx.”

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