

Design Exploration of a Transonic Cruise Slotted Airfoil

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A knowledge-based aerodynamic design method, CDISC, has been leveraged for the computational design exploration of the cruise slotted airfoil as a drag-saving technology for single-aisle, transonic transport aircraft. Aerodynamic predictions were generated using the NASA USM3D Reynolds-averaged Navier-Stokes flow solver, and laminar flow assessments were conducted using the NASA BLSTA3D boundary layer profile solver paired with the LASTRAC stability analysis and transition prediction software. The CDISC design method was used to parametrically vary several slotted-airfoil design variables to understand their impact on aerodynamic performance. In addition to establishing best practices for slotted airfoil design, it was observed that the historically noted skin-friction penalty for cruise slotted airfoils was attributed to the low-Reynolds-number boundary layer of the flap. At cruise, this skin-friction penalty negated any potential decrease in pressure drag enabled by the cruise slotted airfoil architecture. This observation led to the development of an Aft-Laminar Multielement Airfoil concept that uses airfoil shaping to promote natural laminar flow on the flap. At cruise conditions, the concept is predicted to offer a 2.7% reduction in sectional drag relative to a fully turbulent supercritical airfoil. Off-design analyses showed that laminar flow could be maintained with near-cruise variations in angle of attack and Mach number, resulting in sustained aerodynamic efficiency improvements and a delay in the drag rise Mach number. A low-speed, high-lift analysis at takeoff conditions predicted a maximum lift coefficient of 2.5 could be achieved by use of a variable-camber leading edge on the main element and simple deflection of the flap. These computationally-predicted benefits have motivated future research toward an aft-laminar cruise slotted wing design as an incremental step toward the application of natural laminar flow technology on transonic commercial transports.

Nomenclature

Acronyms

ALMA	=	Aft Laminar Multielement Airfoil
BLSTA3D	=	Boundary Layer code for Stability Analysis 3D
CDISC	=	Constrained Direct Iterative Surface Curvature
CFD	=	Computational Fluid Dynamics
LASTRAC	=	Langley Stability and Transition Analysis Code
NACA	=	National Advisory Committee for Aeronautics
NASA	=	National Aeronautics and Space Administration
NLF	=	Natural Laminar Flow
USM3D	=	Unstructured Mesh 3D, Navier-Stokes flow solver

Symbols

c	=	Total airfoil chord, ft
c_F	=	Flap element chord, ft
c_M	=	Main element chord, ft
c_d	=	Sectional drag coefficient
$c_{d,p}$	=	Sectional pressure drag coefficient

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$c_{d,f}$	=	Sectional skin-friction drag coefficient
c_l	=	Sectional lift coefficient
c_m	=	Sectional pitching moment coefficient
C_P	=	Pressure coefficient
g_e	=	Slot exit gap, nondimensionalized by total chord
g_i	=	Slot inlet gap, nondimensionalized by total chord
h	=	Leading-edge device hinge line, distance nondimensionalized by total chord
M_∞	=	Mach number
o_F	=	Flap overhang, nondimensionalized by total chord
$(r/c)_{LE}$	=	Leading-edge radius normalized by local chord
Re	=	Reynolds number
$(t/c)_{max}$	=	Maximum thickness-to-chord ratio
$(t/c)_{TE,M}$	=	Trailing-edge thickness of main element, nondimensionalized by total chord
$(t/c)_{TE,F}$	=	Trailing-edge thickness of flap, nondimensionalized by total chord
x/c	=	x-location nondimensionalized by chord
z/c	=	z-location nondimensionalized by chord
α	=	Angle of attack, degrees
δ_F	=	Flap deflection, degrees
δ_{LE}	=	Leading-edge main element deflection, degrees
γ	=	Slot inlet-to-exit gap ratio, nondimensional
λ	=	Midchord wing sweep, degrees

I. Introduction

GIVEN the desire to reduce the environmental impact of commercial transport aircraft, the aerospace industry is in continuous pursuit of configurations and technologies aimed at significantly reducing the noise, emissions, and fuel consumption of next-generation vehicles. In particular, fuel consumption reductions may be achieved by reducing aircraft empty weight and/or increasing aerodynamic cruise efficiency [1]. One potential concept targeting efficiency improvements is the cruise slotted airfoil. As illustrated in Fig. 1, a cruise slotted airfoil consists of two elements: a main element in the forward-chord region and a flap element in the aft-chord region. These two elements are separated by a slot that serves to redirect stream air from the main element lower surface to the low-momentum, upper-surface boundary layer on the flap. The goal of these airfoils is to enable greater aft loading, relative to conventional supercritical airfoils, by permitting a stronger aft pressure recovery without shock-induced separation. Ultimately, the cruise slotted airfoil is a passive technology that may be used to increase the drag divergence Mach number and/or increase aerodynamic cruise efficiency. These aerodynamic benefits may be realized at the vehicle level through a tradespace that includes the following design options: increasing cruise Mach number, increasing wing thickness, decreasing wing sweep, increasing lift coefficient, and/or decreasing drag coefficient. Increasing the drag rise Mach number would allow for an aircraft to cruise at a higher speed with a limited increase in total aircraft drag. Alternatively, a thicker wing would allow for a lighter wing structure and greater fuel volume. Reduced wing sweep could provide a lighter wing structure and a greater potential for Natural Laminar Flow (NLF) due to an inherent ability to suppress the growth of modal instabilities that often lead to turbulent transition [2]. Increasing the lift coefficient would allow for increased weight, such as fuel for longer duration missions, or cruise at a higher altitude. Finally, decreasing the drag coefficient would enable a reduction in fuel consumption and increased range.

The cruise slotted airfoil was originally proposed in 1965 by Richard Whitcomb and Larry Clark of the National Aeronautics and Space Administration (NASA) Langley Research Center as a technology that could be paired with the well-known supercritical airfoil to increase the drag rise Mach number and allow for commercial aircraft to cruise at higher speeds [4]. Whitcomb and Clark primarily relied on intuitive reasoning to design a slotted, supercritical airfoil based on the five following principles: (1) maximize the Mach number at which the shock moves aft of the slot exit, (2) minimize boundary-layer separation on the upper and lower airfoil surfaces up to the drag rise Mach number, (3) minimize shock losses above the upper surface at the cruise Mach number, (4) minimize skin-friction drag due to the

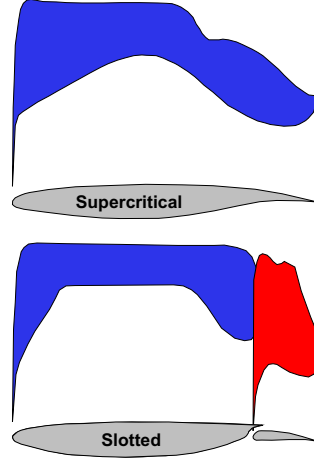


Figure 1. Notional pressure distributions for supercritical and slotted airfoils at cruise (adapted from [3]).

slot, and (5) provide satisfactory off-design performance. Wind tunnel tests conducted in the Langley 8-Foot Transonic Pressure Tunnel were able to substantiate the expected aerodynamic performance of the slotted airfoil with an increase in the drag rise Mach number from 0.67 to 0.79 at the design section lift coefficient with only a 10% increase in drag relative to a traditional National Advisory Committee for Aeronautics (NACA) 642A215 airfoil. Remarkably, these improvements in aerodynamic efficiency were attained without the use of computational design methods. Later research found that boundary-layer separation could be drastically reduced without the use of a slot by tailoring the upper surface pressure distribution alone [5]. Due to its relative simplicity, the single-element supercritical airfoil has become widely used in commercial transports since the 1970s as a means of increasing cruise Mach number [6].

In the early 2000s, collaborative research between Boeing and the NASA Langley Research Center was conducted to verify the performance benefits for full-span [7] and partial-span [8] slotted wing commercial transports via CFD analyses and wind tunnel tests. A partial-span slotted wing was successfully designed, producing a cruise speed increment of $\Delta M = 0.03$ with a 1% improvement in aerodynamic efficiency relative to a conventional wing. While the design provided satisfactory high-lift and stability and control characteristics, it was noted that reducing the skin-friction drag penalty during climb would be desirable. Noted challenges included the slot sensitivity to small changes, structural complexity due to slot brackets, and accurate load predictions in the presence of complex, viscous flow interactions [3]. The primary recommendation was the need to perform system-level assessments to reduce production application risks. Most importantly, the study focused on evaluating the technology's ability to increase the cruise Mach number of a long-range, twin-aisle aircraft with limited consideration of alternative design trades or configurations.

The overarching goal of the present research was to explore the potential of the cruise slotted airfoil concept as a drag-saving technology at flight conditions representative of single-aisle transonic commercial transports. A knowledge-based aerodynamic design method, CDISC, was used in conjunction with the Unstructured Mesh 3D (USM3D) Navier-Stokes flow solver to perform a two-dimensional (2D) parametric exploration of various slotted-airfoil design variables to better understand their impact on aerodynamic performance and identify cruise slotted airfoil design rules that allow for improved aerodynamic efficiency relative to supercritical airfoils.

II. Method

A flow chart of the design and analysis process implemented in this work is illustrated in Fig. 2. The process utilizes a flow solver, grid manipulation tools, a design module, and transition prediction software. The primary design and analysis modules are shown in red, whereas auxiliary output information is shown in blue. The design loop begins with generating an initial flow solution for the baseline airfoil at the flight condition of interest. The extraction module obtains the surface geometry, pressure distribution, and skin-friction data. The design module is then used to modify the airfoil shape to better match a target pressure distribution and/or, in the case of a multielement airfoil, orient and position the aft flap element via user-specified values. The transition prediction loop reads in the airfoil geometry and pressure distribution and uses this information to predict the chordwise extents of natural laminar flow at the flight conditions of interest. This transition information is passed to the flow solver to generate forced laminarization simulations.

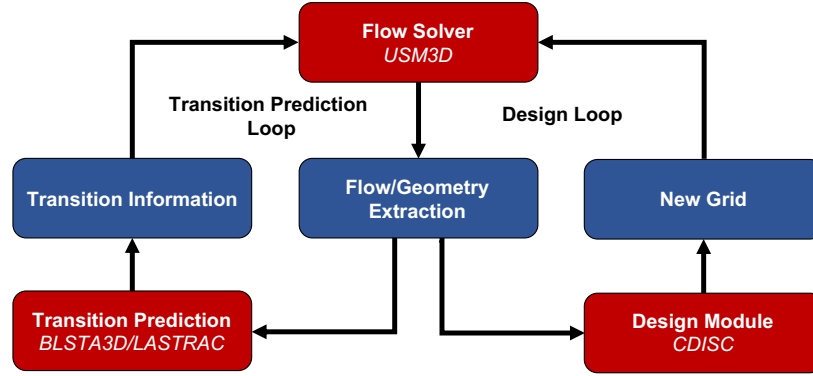


Figure 2. Flow chart of the design and analysis process.

A. Flow Solver

The NASA USM3D flow solver is an all-tetrahedral, cell-centered, Reynolds-averaged Navier-Stokes solver [9] and was used to generate fully turbulent and forced laminarization solutions. One-cell-wide, tetrahedral-cell grids were generated for both conventional supercritical and cruise slotted airfoils as detailed in Section III using VGRID, a grid generation software as part of TetrUSS (Tetrahedral Unstructured Software System) [9]. Inviscid fluxes were computed with Roe's flux-differencing scheme, and the min-mod flux limiter was used to provide numerical stability for 2D grid simulations at transonic flow conditions. The Spalart-Allmaras (SA) one-equation turbulence model was used to model regions of turbulent flows. Forced laminarization simulations were used to model laminar flow ahead of predicted transition fronts to properly model the reduced skin-friction and boundary layer thickness properties of laminar flow regions.

B. Design Module

The design module selected for this study is CDISC [10], a knowledge-based design method compatible with USM3D, among many other 2D/3D flow solvers. CDISC uses flow-geometry sensitivity derivatives, predetermined from empirical and analytical studies, to estimate the geometry changes needed to minimize the difference between current and target pressure distributions. This computationally efficient design approach eliminates the need to numerically calculate sensitivity derivatives and allows the design to converge in parallel with the flow solution. The CDISC method has had extensive use for both turbulent and NLF configuration designs at transonic and supersonic conditions [11, 12]. CDISC flow constraints are available to enforce a variety of engineering design variables, including: sectional force and moment coefficients, spanwise load distributions, and shock location/strength. Additionally, geometry constraints are available to address structural and manufacturing requirements, including: thickness, curvature, volume, and leading-edge radius. For slotted airfoils, geometry constraints related to the orientation and position of the aft flap element were leveraged to perform a parametric design variable exploration as detailed in Section III.

C. Transition Prediction

For laminar-flow predictions, transition front information was generated using BLSTA3D (Boundary Layer code for Stability Analysis 3D)[13] and LASTRAC (Langley Stability and Transition Analysis Code) [14]. BLSTA3D provides the required boundary layer temperature and velocity profiles based on a design airfoil geometry and its associated pressure coefficient distribution. These boundary layer profiles are exported to LASTRAC for stability analyses, which calculates the growth of both Tollmien-Schlichting (TS) and crossflow (CF) modal instabilities. In the present research, stability calculations are based on the Linear Stability Theory (LST) e^N method with compressibility effects included. Because the scope of this research is limited to 2D cruise slotted airfoil assessments, CF growth is not a significant modal instability, and transition becomes limited by TS growth. This TS growth is used to provide a predicted extent of laminar flow along the airfoil based on a user-prescribed critical N-factor (NF). The critical N-factor chosen for this research was a value of 9, which is a typical assumption for a transonic flight environment. In the present research, transition predictions were conducted outside of the design loop as only laminar flow assessments were made for existing designs.

III. Slotted Airfoil Design Exploration

The design of efficient cruise slotted airfoils offers both advantages and challenges relative to the design of conventional airfoils. The primary aerodynamic advantage is the ability to carry more aft loading without boundary layer separation, which could allow for a weaker shock and a reduction in wave drag at a given lift coefficient. The main challenge, especially when using knowledge-based design, is that the number of design variables is significantly increased due to the addition of a slot and flap element. To adequately assess the potential drag-reduction benefits of the cruise slotted airfoil, it is necessary to develop a better understanding of the aerodynamic flow characteristics in relation to the design variables and identify an appropriate design strategy for specifying these variable values. The following subsections will describe the slotted-airfoil design variables, design exploration strategy and results, and a performance comparison between a cruise slotted airfoil and modern supercritical airfoil.

A. Design Variables

Figure 3 defines the slotted airfoil architecture and design variables. The slotted airfoil is defined by a main element, flap element, and intermediate slot, which separates the main element lower surface and flap upper surface. In addition to the typical airfoil design variables, such as thickness, camber, and leading-edge radius, seven additional variables have been identified as key parameters for defining the slotted airfoil. As shown in Fig. 3(b), the new variables are flap overhang (o_F), flap chord (c_F), flap deflection (δ_F), slot exit gap (g_e), slot inlet gap (g_i), and trailing-edge thicknesses for the main element ($(t/c)_{TE,M}$) and flap ($(t/c)_{TE,F}$). Definitions for each of the design variables, as well as prior intuition regarding their specification is listed below.

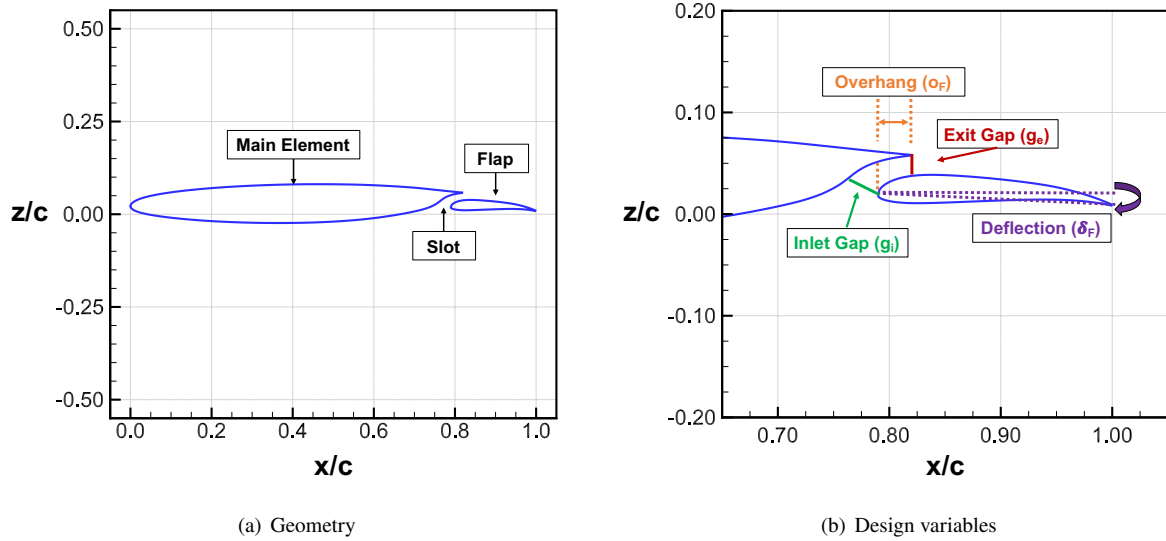


Figure 3. (a) Slotted airfoil geometry and (b) design variables.

1. Flap Chord

Flap chord follows standard airfoil definition as the linear distance between the leading and trailing edges, normalized by total airfoil chord. From an aerodynamic perspective, the flap chord length has a direct impact on the relative loading between each element. For a given flap overhang, the flap chord implicitly defines the main element chord, such that any increase in flap chord leads to a decrease in main element chord and a subsequent decrease in the lift-generating capability of the main element. However, for a given flap loading profile, any increase in flap chord would yield a greater lift contribution and decrease the main element lift required to reach the design lift coefficient. A decrease in flap chord leads to an increase in main element chord, approaching the capabilities of conventional supercritical airfoils with the added expense of skin-friction drag. An increasingly large flap chord could lead to a main element chord that is too small, such that the airfoil shock is either further forward than that of conventional airfoils or aft of the slot, which could lead to boundary layer separation and an increase in drag. Selection of an appropriate chord length becomes a balance between maximizing aft loading, while permitting a weaker main element shock relative to conventional supercritical airfoils.

2. Main Element Trailing-Edge Thickness

The main element trailing-edge thickness, $(t/c)_{TE,M}$, is defined as the trailing-edge thickness of the main element normalized by total chord. Typically, conventional airfoils are primarily concerned with the impact of trailing-edge thickness on aft-chord, boundary-layer separation characteristics when the flow is recovered to freestream conditions. In the case of the slotted airfoil, the highly cambered lower surface of the main element leads to a flow acceleration up to near sonic levels, resulting in a pressure coefficient that is strongly negative relative to supercritical airfoils. The result is an aft-facing trailing edge surface in the vicinity of a near-sonic main element wake that yields a base drag penalty. The main element trailing-edge thickness variable should be minimized, as deemed structurally feasible, to reduce the elemental base drag. The primary design question then becomes whether or not decreasing trailing-edge thickness has any unforeseen negative impacts on the flow through the slot or along the flap element.

3. Flap Trailing-Edge Thickness

The flap element trailing-edge thickness, $(t/c)_{TE,F}$, is defined as the trailing-edge thickness of the flap normalized by total chord. Given that the flap element is responsible for providing a pressure recovery to freestream conditions, it follows that any design principles established for conventional supercritical airfoils would be relevant when specifying the flap trailing-edge thickness. In 1990, Charles Harris of the NASA Langley Research Center published a report summarizing the supercritical airfoil development program and its resulting design guidelines [6]. On the effects of trailing-edge thickness, Harris cited that the minimum transonic drag point was achieved when the pressure coefficient over the upper surface recovered to approximately zero at the trailing edge with a trailing-edge thickness equal to or slightly less than the local upper-surface, boundary-layer displacement thickness. Using this established design knowledge, it would be appropriate to estimate the boundary-layer displacement thickness of the flap element using turbulent flat plate boundary layer theory and leverage this as a default value.

4. Flap Overhang

Flap overhang is defined as the horizontal distance between the flap leading edge and the main element trailing edge, normalized by total chord. The overhang parameter is significant as it implicitly defines the slot length. Increased aft loading may be achieved through two principles: (1) increasing the main element aft loading using greater camber without promoting boundary layer separation on the main element lower surface, and (2) sustaining a near sonic loading on the flap upper surface for the greatest chordwise extent possible without causing a pressure recovery gradient strong enough to cause separation. Based on these principles, the slot is responsible for accelerating the flow from a velocity much lower than freestream on the main element lower surface to a near sonic Mach number at the flap leading edge. Maximum aft loading is achieved when the flow is accelerated as quickly as possible, which may be achieved by minimizing the slot length. Furthermore, any increase in slot length leads to greater skin-friction drag. The implication of a shorter slot length is greater slot curvature. The constraint for minimum slot length is likely to be a practical consideration in relation to manufacturability and/or structural limitations.

5. Slot Exit Gap

The slot exit gap is defined as the vertical distance between the main element trailing edge and the flap upper surface, normalized by total chord. The mechanisms by which the slot prevents boundary layer separation have been detailed in prior studies [7, 8, 15]. At the main-element trailing edge, the upper- and lower-surface boundary layers combine to form a wake that traverses above the upper surface of the flap. The wake generated contributes to any aft-chord pressure recovery while remaining resistant to flow reversal due to turbulent mixing. The upper-surface boundary layer on the flap remains fairly thin due to its relatively short chord length. Pairing these flow features results in an ability to provide a steeper pressure recovery without separation relative to supercritical airfoils. Richard Whitcomb's prior research on slotted airfoils led to the observation that the wake was able to traverse above the flap distinctly from the upper-surface boundary layer for slot exit gap values approximately twice that of the main element lower surface boundary layer thickness at the trailing edge [4]. The primary research questions regarding the slot exit gap variable then becomes: for what gap values do the CFD simulations predict a distinct main element wake, and what is the resulting impact on the airfoil pressure distributions?

6. Slot Inlet Gap

The slot inlet gap is defined as the shortest distance between leading edge of the flap and the maximum surface slope point on the main element lower surface, normalized by total airfoil chord. For the current study, the inlet-to-exit gap ratio ($\gamma = g_i/g_e$) was defined as an alternative design variable for specifying the 2D slot area distribution. In effect, the slot region becomes analagous to a convergent nozzle, for which the gap ratio may be tailored to yield favorable flow acceleration characteristics. For the design exploration, the goal is to understand how the gap ratio impacts the pressure distributions on the main element lower surface and flap upper surface and whether an optimal ratio exists that may be used as a design rule within CDISC.

7. Flap Deflection

Flap deflection is defined as the flap incidence angle, measured in degrees, relative to the zero-angle-of-attack reference line. An increase in flap deflection will increase the flap angle of attack, resulting in an increase in flap loading. An increase in flap deflection also yields an increase in the effective angle of attack for the total airfoil, which decreases the zero-lift angle of attack. From a design perspective, one might expect this design variable to have a significant impact on the main element pressure distribution. The questions then become: how does flap deflection impact the main element shock strength and location, and how might flap deflection and main element surface shaping be optimally used together to establish a target shock location?

B. Design Exploration Strategy

Many of the key variables, such as slot exit gap, flap overhang, flap deflection, and trailing-edge thickness, were existing constraints within CDISC. One new constraint was added to shape the main element lower surface to obtain a desired inlet-to-exit gap ratio. A parametric design exploration of these variables was conducted to build intuition of their impact on the airfoil pressure distributions and aerodynamic force and moment coefficients. Once key design rules are identified, these geometry constraints can then be manually set to maintain their empirically-guided values while CDISC shapes the airfoil elements based on flow constraints to improve aerodynamic performance.

The objective of this research was to explore the drag-saving potential of the cruise slotted airfoil in application to transonic, single-aisle transport aircraft. In support of this effort, the flight conditions and geometric characteristics of the Common Research Model (CRM)[16], a generic twin-aisle transport model widely used for computational design research, were scaled to be representative of a single-aisle transport aircraft with a cruise Mach number of 0.8. Table 1 lists the flow conditions and geometry characteristics used in the present study, in addition to the 2D-scaled equivalent values. In 3D, the Mach and Reynolds number are consistent with a single-aisle transport aircraft cruising at an altitude of 40,000 ft. The geometry parameters and sectional lift requirement were estimated to be consistent with that of an outboard section of a supercritical wing, resulting in a midchord sweep of 22.6 degrees, maximum thickness-to-chord ratio of 0.096, and a sectional lift requirement of 0.673. In 2D, the Reynolds number (Re), Mach number (M), sectional lift coefficient (c_l), and maximum thickness-to-chord ratio ($(t/c)_{max}$) were scaled using simple sweep theory.

Table 1. 3D and 2D-scaled parameters for computational design exploration.

Parameter	3D	2D
M_∞	0.800	0.739
Re	14.9×10^6	12.7×10^6
λ	22.6°	0°
c_l	0.645	0.756
$(t/c)_{max}$	0.096	0.104

C. Baseline Slotted Airfoil

In support of the 2D parametric study, it was necessary to develop a baseline slotted airfoil using initial values for the seven previously noted design variables in Section III.A. While CDISC may be used in its current state to parametrically change each of these design variables, it was not capable of defining a baseline slotted airfoil architecture. For this reason, a new MAKESLOT code was developed to create a slotted airfoil from a baseline conventional airfoil while satisfying the user-defined slotted-airfoil design variable values.

The MAKESLOT code reads in a conventional airfoil geometry and the desired values for the seven slotted-airfoil design variables, then begins with the definition of the flap geometry, location, and orientation. An elliptical nose upper surface is defined for the overhang region, with the vertical axis determined as a function of the original airfoil $(t/c)_{\max}$. The center of the ellipse is translated vertically to achieve the specified slot exit gap dimension. The lower surface of the nose is also an ellipse with the vertical axis reduced to 40% of the upper surface axis. Bicubic fairings extend from the end of these nose segments to the upper and lower surface trailing edge points, positioned to give the desired $(t/c)_{TE,F}$. Additional camber is added to give the flap more of a supercritical airfoil profile, and the flap is then sheared about the leading edge to obtain the desired flap deflection.

For the main element, the original upper surface is retained aft to a point located by adding the desired overhang distance to the flap leading edge location. The lower surface trailing edge is then located below this point to give the prescribed $(t/c)_{TE,M}$. A new main element lower surface is defined ahead of this point by extending lines normal to the flap nose upper surface with distances varying from the slot exit gap dimension at the trailing edge to the inlet gap dimension normal to the flap leading edge. To improve the surface curvatures, geometry smoothing and a small thickness adjustment is used extending from the slot entrance to the midchord point on the main element. Finally, the modified lower surface is further shaped to obtain the desired inlet-to-exit gap ratio. The original conventional airfoil lower surface is retained forward of the midchord point.

Table 2 lists the default values for each of the slotted airfoil design parameters used to create a baseline slotted airfoil. The overhang was arbitrarily chosen to be $0.04c$, as it provided a reasonable balance between slot length and curvature. A flap chord was defined to be $0.22c$, which implicitly defines the main element trailing edge to be located at $0.82c$ with the slot centered at $0.80c$. The rationale was to specify a sufficient flap chord length, such that it would be capable of providing a greater aft loading compared to the conventional airfoil, yet a large enough main element chord to allow for a more aft shock location without translation aft of the slot exit. The flap deflection of 3 degrees was arbitrarily selected based on the idea that the flap loading should be maximized without inducing supersonic flow on the flap upper surface. Such a loading profile would likely require a nonzero flap incidence angle. Since the flow on the main element lower surface must be accelerated from less-than-freestream velocities to a near sonic Mach number at the slot exit, a gap ratio value of 1.5 was chosen in analogy to the 2D convergent nozzle principle. Based on the design guidelines noted by Harris [6], the trailing-edge thicknesses of the main and flap elements were consistently set based on flat plate turbulent boundary layer theory estimates for displacement thickness on the flap upper surface near the trailing edge using the 2D-scaled flow conditions.

Table 2. Baseline slotted-airfoil design variable values.

o_F	c_F	δ_F	g_e	γ	$(t/c)_{TE,M}$	$(t/c)_{TE,F}$
0.04	0.22	3°	0.20	1.5	0.0010	0.0010

D. Computational Grids

One-cell-wide, tetrahedral-cell computational grids were generated using VGRID for baseline conventional and slotted airfoils as shown in Fig. 4. The conventional supercritical airfoil matches the thickness-to-chord value of 0.104 as specified in Section III.B, whereas the slotted airfoil geometry was derived from the conventional airfoil using the MAKESLOT code described in the previous section. Each grid was generated based on the 2D flow conditions using a cell-centered $y^+ = 1$ with approximately 30 viscous cell layers. For both grids, volume sources were added to the leading and trailing edges to better resolve the airfoil stagnation points. In the case of the slotted airfoil, a cylindrical volume source was centered about the flap to better resolve the wake emanating from the main element. Additionally, a gap-based volume source (not observable) was added in the vicinity of the slot to resolve the complex, viscous flow interactions between the two elements.

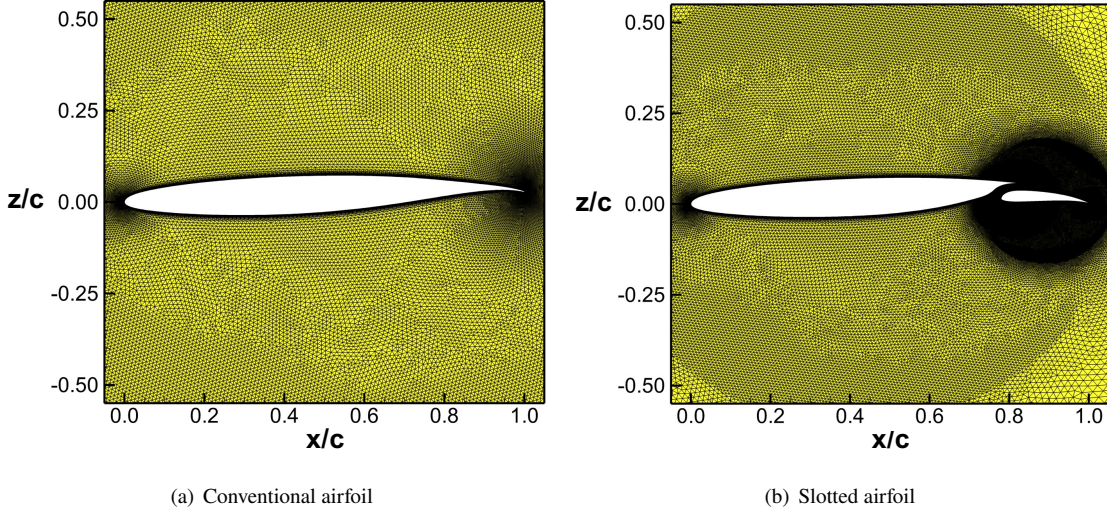


Figure 4. Grids generated for baseline (a) conventional and (b) slotted airfoils.

E. Parametric Study

The approach adopted for the slotted-airfoil design exploration was to parametrically vary each design parameter in an attempt to build intuition as to how each variable impacts the airfoil pressure distributions and aerodynamic force/moment coefficients. CDISC is used to independently vary each design variable of interest while holding all others constant. For each design perturbation, 10K flow iterations were simulated in USM3D to achieve a converged solution, after which the angle of attack was adjusted to match the design c_l . The following subsections summarize the variable values explored and aerodynamic trends observed for each design parameter. In the present study, the flap trailing-edge thickness was not investigated due to the established design guidelines for conventional airfoils.

1. Main Element Trailing-Edge Thickness

The $(t/c)_{TE,M}$ values chosen for the parametric design exploration were [0.0005, 0.0010, 0.0020, and 0.0030]. Relative to the baseline value of 0.0010, a smaller value of 0.0005 was chosen since this value was consistent with an earlier investigation of the slotted airfoil design by Richard Whitcomb in the 1960s [4]. The upper range value of 0.0030 was consistent with the main element trailing-edge thickness value of the CRM. As mentioned earlier, trailing-edge thickness values for conventional airfoils have been typically set using design guidelines based on the boundary layer characteristics at the trailing edge in an attempt to avoid separation. However, the main element trailing edge is not responsible for a complete pressure recovery to freestream conditions, as it maintains a substantially negative pressure coefficient. Thus, the chosen parametric values encompass a practical range for trailing-edge thickness.

Figure 5 shows the pressure distributions and airfoil geometries for $(t/c)_{TE,M} = [0.0005, 0.0010, 0.0020]$, where the critical pressure coefficient is denoted by a horizontal gray dashed line. This subset of values was chosen to highlight the primary trends observed. The main element pressure distribution is generally characterized by a slightly supersonic rooftop with an aft shock terminating near $x/c = 0.7$. Changes in main element trailing edge thickness were observed to have relatively little impact on the pressure distribution with only slightly higher velocities on the aft upper surface due to a decrease in surface slope from the airfoil shearing. This subsequently leads to greater velocities on the flap near the main element trailing edge. The overall effect on flow velocity appears to diminish for decreasing thickness values, with little difference between $(t/c)_{TE,M} = 0.0005$ and 0.0010. Figure 6 shows the resulting sectional drag and pitching moment coefficients. The sectional drag demonstrates a nearly linear decrease with decreasing thickness values. Because the loading between the two elements remains relatively constant, the sectional pitching moment shows little variability with changes in main element trailing-edge thickness. Overall, these results support the theory that main element trailing-edge thickness should be minimized to reduce the base drag penalty associated with cruise slotted airfoils, subject to practical manufacturing constraints.

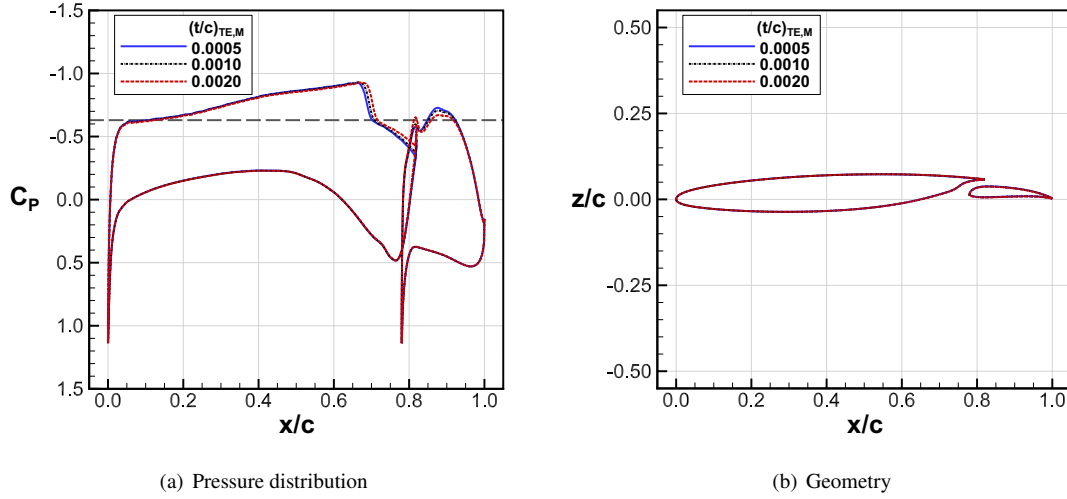


Figure 5. USM3D results for the parametric study of main element trailing-edge thickness, $(t/c)_{TE,M}$: (a) pressure distributions and (b) airfoil geometries.

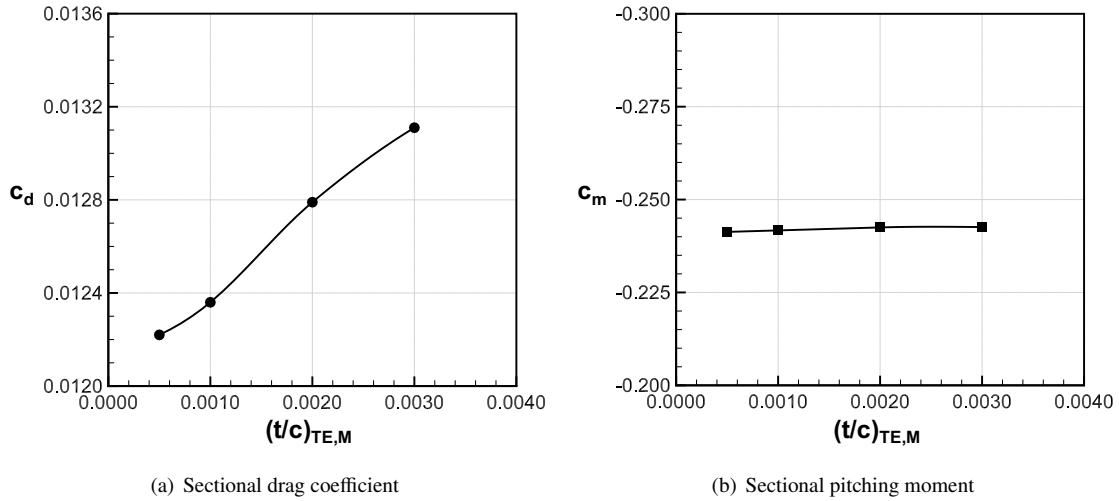


Figure 6. USM3D results for the parametric study of main element trailing-edge thickness, $(t/c)_{TE,M}$: (a) sectional drag coefficients and (b) pitching moment coefficients.

2. Slot Exit Gap

To maximize the ability of the flap to sustain a strong pressure recovery gradient, it was noted that the slot exit gap must be large enough such that the main element wake could traverse above the upper surface of the flap distinctly from the flap boundary layer. Prior research [4] by Richard Whitcomb suggested that the exit gap be specified as a multiple of the boundary layer thickness on the main element lower surface near the trailing edge. Whitcomb's recommendation was to set the gap as approximately twice that of the boundary layer thickness. For the current flow conditions, turbulent flat-plate boundary-layer theory estimates the main element boundary-layer thickness to be $0.012c$. The g_e values chosen for the parametric design exploration were $[0.014, 0.016, 0.018, 0.020, \text{ and } 0.022]$, which reflects a range of 1.2 to 1.8 times the estimated boundary-layer thickness. USM3D simulations were used to computationally verify the threshold for which the main element wake is able to traverse freely and identify an empirical guideline for specifying exit gap values.

Figure 7 shows the pressure distributions and airfoil geometries for $g_e = [0.014, 0.018, 0.022]$. The main element upper surface pressure distribution remains virtually unchanged for each gap value. For successive increases in gap, the lower surface exhibits a slight increase in midchord velocity followed by lower velocities leading into the slot entrance. This result can be attributed to holding the slot inlet-to-exit gap ratio constant. As the exit gap is increased, the inlet gap is also increased. Pairing this with the CDISC gap ratio constraint's internal smoothing of the main element leads to a more gradual change in aft camber and a subsequent increase in main element aft loading. For successive increases in gap, the flow through the slot gradually accelerates to near sonic levels with minimal variation in flap loading. Figure 8 shows the resulting sectional drag and pitching moment coefficients for each parametric value of slot exit gap. Consistent with the flow features shown in the pressure distribution plot, the sectional drag coefficient is relatively constant for lower gap values until it increases to a point where near supersonic flow is encountered on the upper surface of the flap. The sectional pitching moment exhibits slightly more negative values or greater aft loading for increases in slot exit gap. This result may be attributed to the increase in main element aft loading due to the previously noted cambering effect.

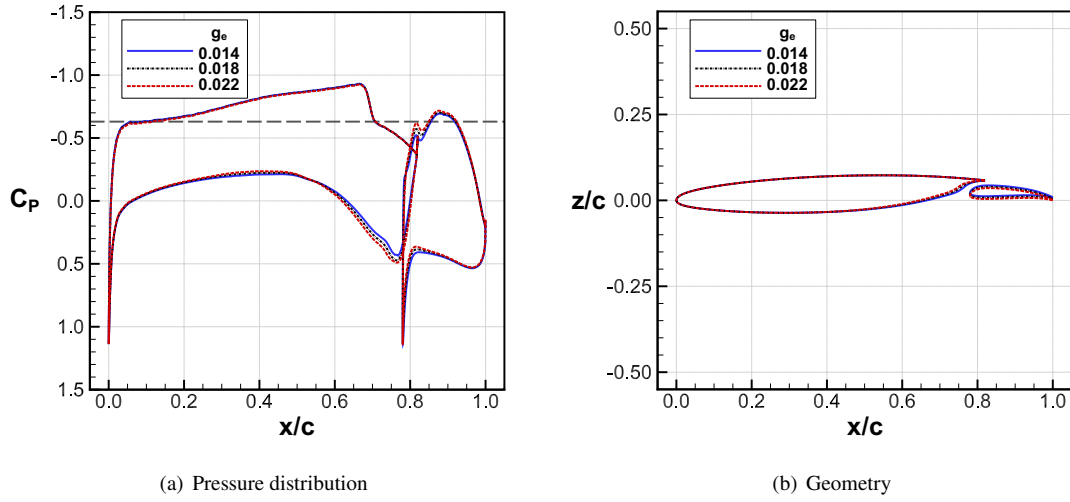


Figure 7. USM3D results for the parametric study of slot exit gap, g_e : (a) pressure distributions and (b) airfoil geometries.

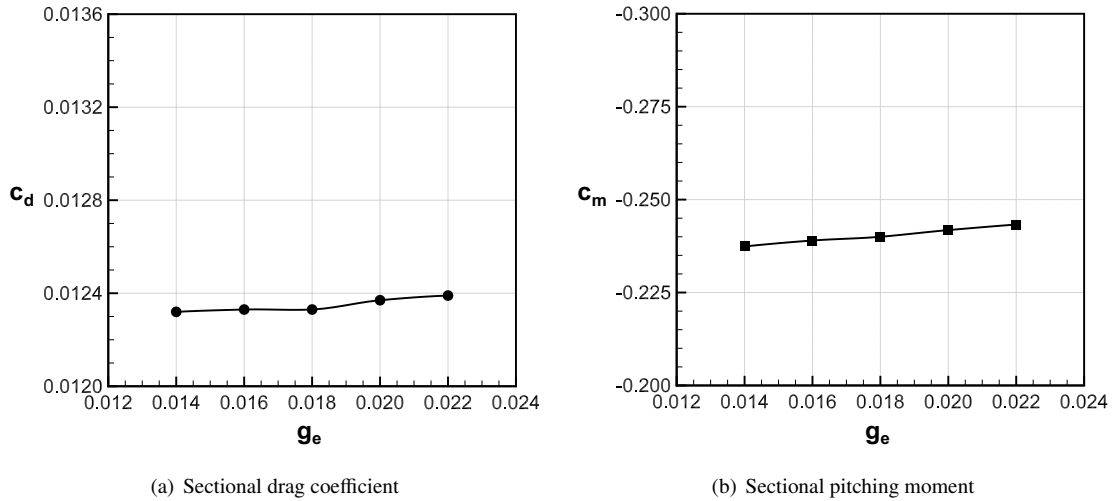


Figure 8. USM3D results for the parametric study of slot exit gap, g_e : (a) sectional drag coefficients and (b) pitching moment coefficients.

To better understand the impact of slot exit gap values on flow interaction between the turbulent main element wake and flap boundary layer, USM3D entropy contour data were plotted as seen in Fig. 9. The entropy values range from 0 to 0.020 and were set such that the empirical estimate for main element lower surface boundary layer thickness was visually consistent with the red contour region. For an exit gap of 1.4%, the main element wake appears to merge with the flap boundary layer at approximately 60% of the flap chord. As the gap is increased to 1.8% the buffer between the wake and boundary layer begins to increase with the merge location closer to the flap trailing edge. As the gap increases to 2.2%, the wake and flap boundary layer appear to travel distinctly from each other with limited interaction. These computational results support Richard Whitcomb's empirical guideline that the slot exit gap be approximately a factor of 2 greater than that of the main element lower surface boundary layer thickness at the slot exit. By doing so, wake-boundary-layer interactions can conservatively be mitigated to prevent off-surface separation and increased turbulence.

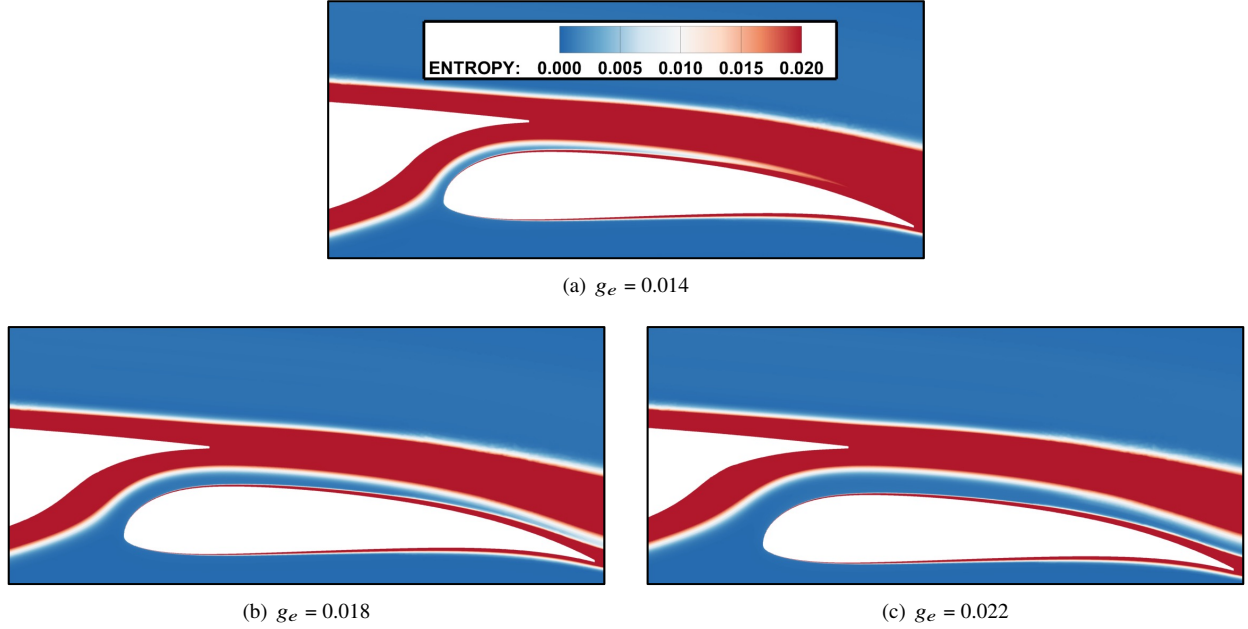


Figure 9. USM3D entropy contours for the parametric study of slot exit gap, g_e .

3. Slot Gap Ratio

The slot inlet-to-exit gap ratio values chosen for the parametric design exploration were [1.3, 1.4, 1.5, 1.6, and 1.7]. Figure 10 shows the USM3D pressure distributions and airfoil geometries for $\gamma = [1.3, 1.5, 1.7]$. The main element upper surface pressure distribution is relatively unaffected by changes in gap ratio. Similar to the exit gap study, the main element lower surface is characterized by a decrease in velocity leading up to the slot for increased gap ratio values. Intuitively, this might be expected as in both cases the slot inlet gap is varying due to changes in either the slot exit gap (with a constant γ) or the slot inlet-to-exit gap ratio (with a constant g_e). One important observation that differs from the slot exit gap study is that the minimum velocity encountered on the main element lower surface varies with changes in gap ratio. For greater gap ratios, the "pressure bucket" on the lower surface expands, leading to greater aft loading. In contrast to the exit gap study, increasing the slot gap ratio yields continuous decreases in the peak loading near the leading edge of the flap upper surface, though with diminishing returns. Aft of the slot exit, the flap upper surface pressure distribution remains relatively unchanged.

Figure 11 shows the resulting sectional drag and pitching moment coefficients for each parametric value of the slot inlet-to-exit gap ratio. As the gap ratio is increased, the sectional drag remains relatively constant for values below 1.5, but afterward, gradually increases to a maximum at $\gamma = 1.7$. The observed increase in sectional drag for higher gap ratios may be attributed to a decrease in the minimum velocity encountered on the main element lower surface, which could lead to flow separation prior to the slot entrance. Due to increases in main element aft loading, the sectional pitching moment tends to decrease with increasing gap ratio values.

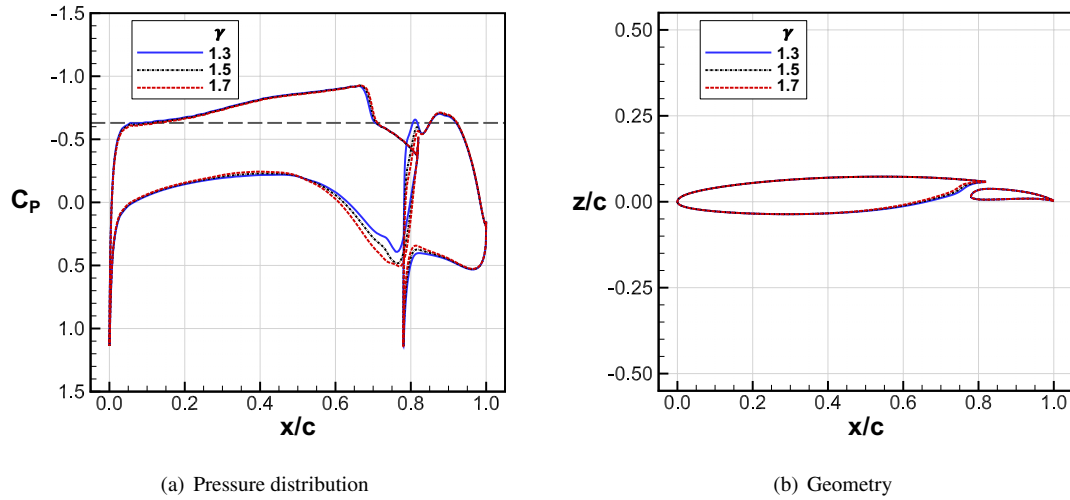


Figure 10. USM3D results for the parametric study of slot inlet-to-exit ratio, γ : (a) pressure distributions and (b) airfoil geometries.

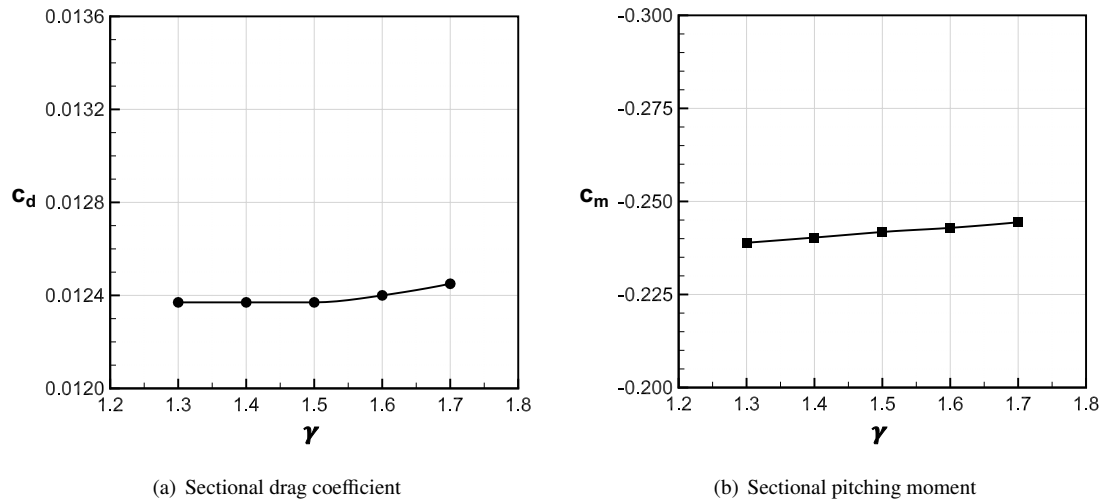


Figure 11. USM3D results for the parametric study of slot inlet-to-exit ratio, γ : (a) sectional drag coefficients and (b) pitching moment coefficients.

4. Overhang

The overhang values chosen for the design exploration were [0.03, 0.04, and 0.05]. A CDISC overhang constraint was used to extend the flap leading edge, while holding the main element trailing edge location fixed, to achieve the desired overhang value. As a result, successive increases in overhang lead to a greater flap chord length but a constant total airfoil chord length.

Figure 12 shows the USM3D pressure distributions and airfoil geometries for each overhang value. The airfoil geometry plot shows the expected increase in flap chord length with increased overhang, in addition to an increase in the aft camber of the main element. As the flap chord is increased, the slot gap ratio constraint reshapes the main element lower surface to keep the slot entrance gap constant. The pressure distribution reflects this increase in main element aft camber with a more pronounced "pressure bucket". Any increase in overhang yields an increase in slot length and a more gradual flow acceleration through the slot. As a result, the aft flap loading appears to decrease; however, this is offset by increases in chord length such that there is a negligible change in the lift contribution. One interesting feature is that the shock on the main element upper surface strengthens and shifts aft by approximately 5% for each 1%-increment in overhang. Because the aft loading of the main element increases, the angle of attack required to meet the required sectional lift decreases as shown by the reduction in flow acceleration near the main element leading edge.

Figure 13 shows the variations in the sectional drag and pitching moment coefficients due to changes in flap overhang. The sectional drag shows a relatively linear increase with greater values of overhang. This sectional drag increase can be attributed to the increase in shock strength and wave drag for greater values of overhang. Similar to the slot gap ratio variable, the increase in aft camber of the main element with increased overhang leads to a reduction in minimum velocity on the main element lower surface, which can increase chances of boundary layer separation. In a similar trend, the sectional pitching moment coefficient decreases linearly with greater values of overhang due to the increase in aft loading of the main element.

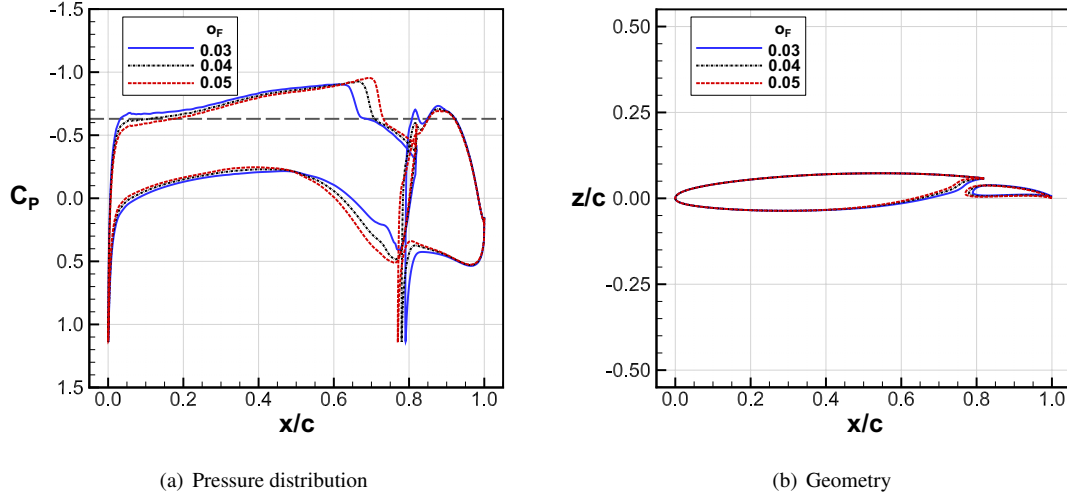


Figure 12. USM3D results for the parametric study of flap overhang, o_F : (a) pressure distributions and (b) airfoil geometries.

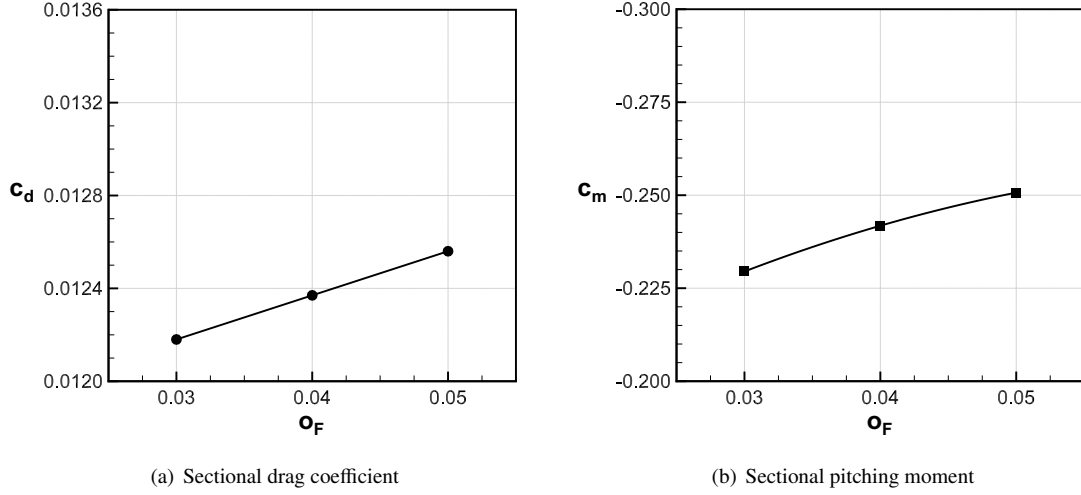


Figure 13. USM3D results for the parametric study of flap overhang, o_F : (a) sectional drag coefficients and (b) pitching moment coefficients.

5. Flap Deflection

Flap deflection values chosen for the parametric design exploration were [1, 2, 3, 4, and 5] deg. Figure 14 shows the resulting pressure distributions and airfoil geometries for $\delta_F = [1, 3, 5]$ deg. This subset of values was chosen to highlight the primary trends observed for the main element and flap. As the flap element is deflected to higher incidence angles, the flap loading increases with the flow on the upper surface reaching supersonic velocities at $\delta_F = 5^\circ$. Furthermore, the pressure gradient on the lower surface of the flap becomes more favorable as the flap is deflected and the lower surface aligns more parallel to the incoming flow. With an increase in flap deflection, the effective angle of attack of the slotted airfoil increases. To maintain the design c_l , the total angle of attack must be reduced for higher deflection angles. This result is reflected in the pressure distributions near the leading edge of the main element with a decrease in leading-edge flow acceleration and reduction in forward-chord lift. Additionally, a rearward translation in shock position on the main element is observed from $x/c = 0.5$ for $\delta_F = 1^\circ$ to $x/c = 0.75$ at $\delta_F = 5^\circ$. From $\delta_F = 1^\circ$ to 3° , the shock strength is relatively constant, whereas from $\delta_F = 3^\circ$ to 5° , the shock becomes noticeably stronger.

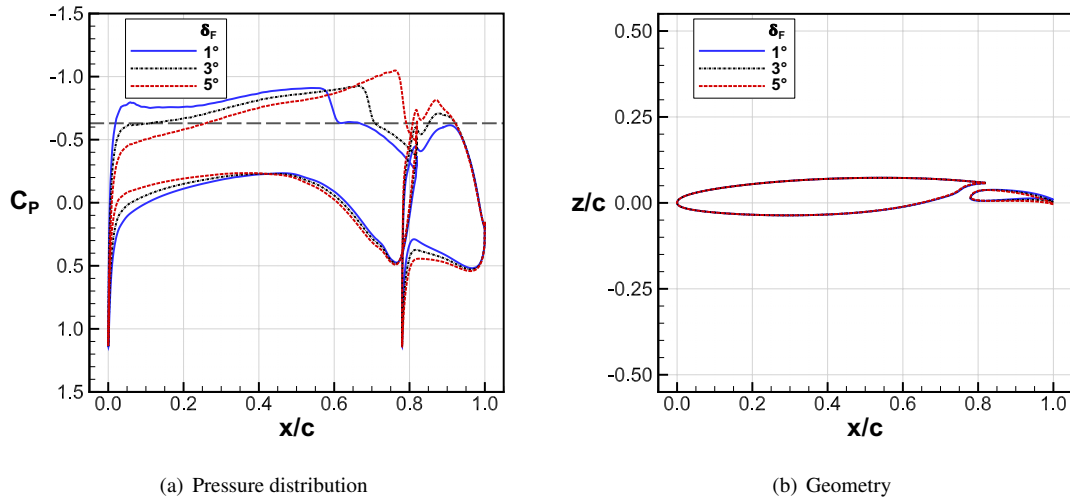


Figure 14. USM3D results for the parametric study of flap deflection, δ_F : (a) pressure distributions and (b) airfoil geometries.

Figure 15 shows the resulting sectional drag and pitching moment coefficients for each value of flap deflection. The sectional drag is observed to increase nonlinearly as the flap is deflected to higher incidence angles. This result may be attributed to an increase in wave drag due to the strengthening of the main element shock and introduction of a shock on flap element. Without any shaping of the main element upper surface, the sectional drag is at a minimum for the lowest deflection angle despite having a more forward shock position. For this geometry, the forward-chord region of the main element is more positively loaded with a forward facing surface, reducing the drag penalty for the given design c_l while limiting the potential for wave drag on the flap due to subcritical velocities. The sectional pitching moment is observed to linearly decrease with deflection angle as the main element shock moves aft and the flap loading increases.

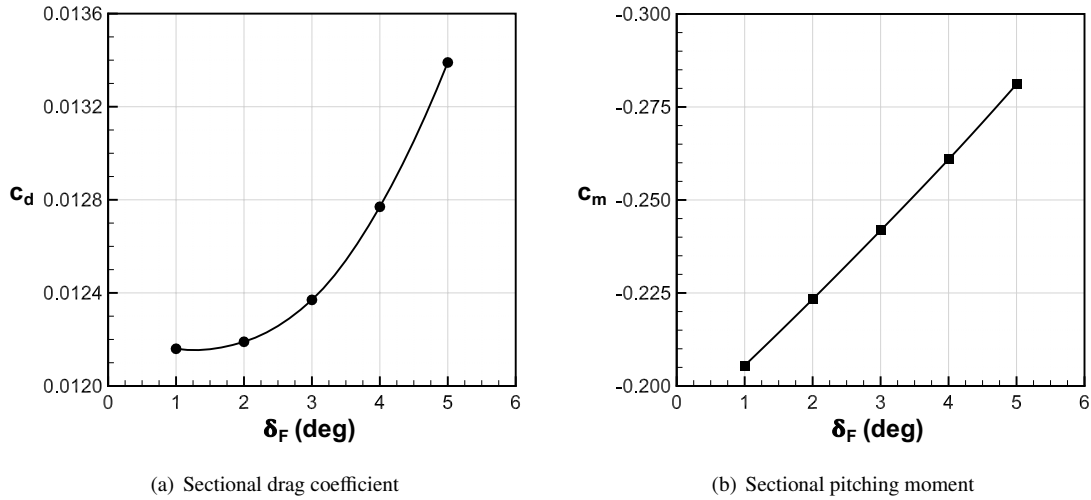


Figure 15. USM3D results for the parametric study of flap deflection, δ_F : (a) sectional drag coefficients and (b) pitching moment coefficients.

F. Design Rules

The observations made as a result of the parametric design exploration may be used to formulate a set of design rules for each slotted airfoil design variable. As an initial design strategy, the expectation is that these parameters may be held constant based on the aforementioned design rules, and CDISC can be used to shape the main element and flap surfaces using the standard transonic airfoil turbulent flow constraints within CDISC. In developing these design rules, the underlying principle is to maximize the flap loading without introducing locally supersonic velocities and increasing the chance of inducing boundary layer separation. The empirical design rules developed in support of this design strategy are described as follows:

- 1) The main element trailing-edge thickness should be minimized to reduce the base drag penalty associated with the baseline cruise slotted airfoil. The parametric study showed a linear decrease in sectional drag with decreasing trailing-edge thickness values. Because of the slot exit velocity, the main element is not responsible for recovering the flow to ambient conditions and can be reduced without concern for boundary layer separation. Though, manufacturing capabilities may serve as a practical limitation for tolerable thickness values. For the present study, a minimum thickness value of $0.0005c$ was chosen to avoid potential grid movement issues.
- 2) The slot exit gap should be set to a threshold value of at least 1.8 times the boundary layer thickness of the main element lower surface at the trailing edge. For exit gap values greater than or equal to the proposed value, the wake from the main element is able to traverse independently above the upper surface boundary layer of the flap. A boundary layer analysis was conducted on the CFD solutions, and the computationally-predicted boundary layer thickness was in close agreement with empirical estimates based on flat plate turbulent boundary layer theory. The default constraint value within CDISC may be estimated using flat plate theory boundary layer estimates, in conjunction with the design guideline. This rule is largely in agreement with prior research by Whitcomb [4].

- 3) The flap overhang should be held fixed, and the slot gap ratio should be increased until reaching a skin-friction coefficient of 1 count at the slot entrance. The parametric study showed that increasing the flap overhang leads to an increase in flap chord and slot length with a more gradual flow acceleration through the slot and an increase in main element aft camber. However, flow changes were not limited to the slot as the main element upper surface shock also increased and shifted aft. In contrast to overhang, changes in gap ratio do not lead to changes in the flap chord length, only changes in the slot area compression rate. While increasing the slot gap ratio does increase the main element aft camber, flow changes are more localized to the slot with negligible changes to the main element shock location/strength. The design recommendation was proposed to increase the aft loading of the airfoil while avoiding boundary layer separation on the main element lower surface.
- 4) The flap deflection should be set based on maximizing the flap loading without introducing supersonic velocities on the flap upper surface. By doing so, this maximizes the aft loading of the airfoil and reduces the required sectional lift contribution of the main element. While the parametric study demonstrated a sectional drag benefit for the lowest deflection values, it is anticipated that a redesign of the main element upper surface based on the turbulent flow constraint will enable a weaker shock resulting in decreased wave drag.

IV. Turbulent Slotted Airfoil Design

Using the intuition gained from the parametric design exploration, the objective was to design a fully turbulent cruise slotted airfoil design using the CDISC design method to quantify its aerodynamic performance at conditions representative of single-aisle, transonic transport aircraft. However, prior to designing a cruise slotted airfoil, it was necessary to design a supercritical airfoil to establish representative aerodynamic performance achievable with modern design approaches. The following section reviews the CDISC design strategy implemented in the development of both the conventional and cruise slotted airfoils and the USM3D predictions for aerodynamic cruise performance.

A. Design Strategy

The CDISC design module automatically generates target pressure distributions based on the current analysis pressures and any user-specified flow or geometry constraints. For the conventional airfoil, a single flow constraint was used to create the target pressure distribution. Various parameterizations of this CDISC flow constraint have been previously documented for laminar and turbulent designs at transonic and supersonic flight conditions [11, 12]. The turbulent flow constraint creates a target pressure distribution characterized by a rapid acceleration of the flow on the upper surface near the airfoil leading edge, followed by an adverse midchord pressure gradient region, ending with a shock located at a point where the surface slope becomes slightly negative. In terms of geometry constraints, the maximum airfoil thickness was held constant, but the leading-edge radius and twist were free to change to better match the target pressure distribution.

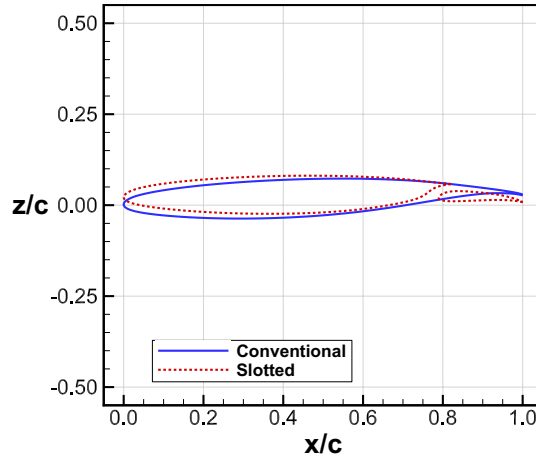
For the cruise slotted airfoil design, the same flow and geometry constraints were used to design the main element upper surface. The design rules established in Section III.F were implemented within CDISC to position the flap element and shape the slot. The trailing-edge thickness of the main element was decreased from the baseline value of 0.001c to 0.0005c to reduce the base drag penalty associated with multielement airfoils. The overhang was held constant at a value of 0.03c, the lowest value analyzed in the design exploration, to minimize the slot length. The exit gap was set to 0.02c as this represented a threshold such that the turbulent main element wake was free to traverse above the upper surface of the flap. The gap ratio was set based on meeting a skin-friction drag value of one count at the slot entrance to maximize the main element loading while avoiding separation. Deflection was automatically adjusted between each design cycle until a Mach number of 0.95 was reached near the leading edge of the flap. Aft of the slot, a flow constraint was added to maintain the flap upper surface velocity at Mach 0.95 up to approximately 95% of the total chord before allowing for a pressure recovery to freestream conditions. A load balancing constraint was added such that the main element sectional lift requirement was updated based on the lift contribution of the flap to meet the total sectional lift requirement. The final variable values for the fully turbulent cruise slotted airfoil are summarized below in Table 3.

Table 3. Slotted airfoil design variable values.

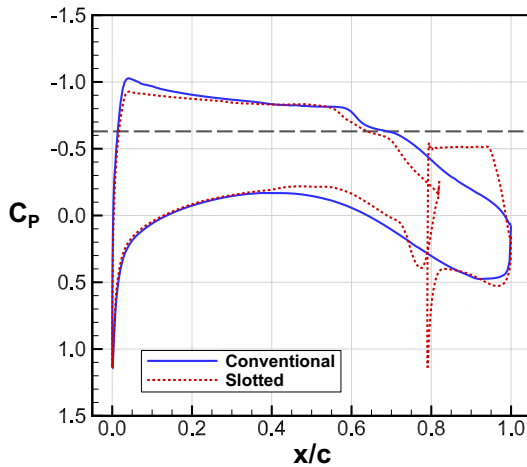
O_F	C_F	δ_F	g_e	γ	$(t/c)_{TE,M}$	$(t/c)_{TE,F}$
0.03	0.21	2.6°	0.20	1.5	0.0005	0.0010

B. Design Results

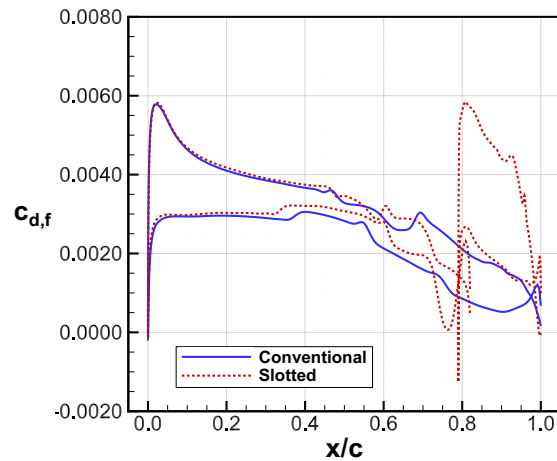
Figure 16 shows the airfoil geometries and USM3D results for the airfoil pressure and skin-friction distributions at the cruise condition. The pressure distribution for the conventional airfoil (blue) is reflective of modern supercritical designs with a rapid acceleration of the flow near the leading edge, followed by a mild adverse pressure gradient, and a weak shock terminating near $x/c = 0.6$. The pressure distribution for the cruise slotted airfoil (red) shows similar flow features on the main element upper surface with a weak shock terminating slightly forward relative to the conventional airfoil. The pressure recovery region on the main element upper surface is much steeper relative to the conventional airfoil but does not recover to freestream conditions due to the increased flow velocity at the slot exit. In terms of flap loading, the pressure gradient on the upper surface is nearly zero as the Mach number was held to a constant value of 0.95. The result is an ability to sustain near supersonic flow up to 95% of the total airfoil chord and an increase in aft loading relative to the supercritical airfoil. While the cruise slotted airfoil allows for an increase in aft loading across the flap region relative to the conventional airfoil, the overall airfoil shock strength and location remains relatively unchanged due to a reduced main element aft loading. The increased aft loading due to the contribution of the flap provides a slightly reduced sectional lift requirement for the main element, and hence, a lower angle of attack relative to the conventional airfoil as reflected by a slightly reduced peak acceleration near the leading edge of the airfoil.



(a) Airfoil geometries



(b) Pressure distributions



(c) Skin-friction distributions

Figure 16. USM3D results for the conventional and slotted airfoil designs: (a) airfoil geometries, (b) pressure distributions, and (c) skin-friction distributions ($M_\infty = 0.739$, $Re = 12.7 \times 10^6$).

In reviewing the skin-friction distributions, it was observed that the historically noted skin-friction penalty of cruise slotted airfoils could not necessarily be attributed to an increase in wetted area due to the introduction of a slot. In reality, the flap element incurs increased skin-friction drag relative to the conventional airfoil over the same chordwise extent. This is not only due to the increased flow acceleration over the flap surface but can be generally explained by the introduction of a new boundary layer on the flap element. Due to the relatively low chordwise Reynolds number of the flap, the skin-friction drag becomes much greater in comparison to the well-developed boundary layer aft of the conventional airfoil. An increase in skin-friction drag by nature of having a multielement airfoil suggests a need to drastically reduce the pressure drag to not only compensate for the skin-friction penalty but yield a net decrease in sectional drag for a fully turbulent airfoil design.

Table 4 shows the the resulting force and moment coefficients at cruise for the fully turbulent conventional and slotted airfoil designs. At the design lift coefficient, the pitching moment for the slotted airfoil is nearly 20% more negative, which is consistent with the increase in aft loading in the vicinity of the flap. However, it is observed that the sectional drag coefficient for the slotted airfoil is 7-counts greater than the conventional airfoil at cruise. This can largely be attributed to the increase in skin-friction drag due to the introduction of a new boundary layer over the flap, in addition to the relatively minor changes in shock strength and thus, wave drag over the main element.

Table 4. Aerodynamic cruise performance for the conventional and slotted airfoils ($M_\infty = 0.739$, $Re = 12.7 \times 10^6$).

Airfoil	Variant	c_l	c_d	$c_{d,p}$	$c_{d,f}$	c_m	α
Conventional	Turbulent Design	0.756	0.0112	0.0053	0.0059	-0.154	0.98°
Slotted	Turbulent Design	0.756	0.0119	0.0050	0.0069	-0.182	1.63°

It is evident that the proposed fully turbulent cruise slotted airfoil is unable to provide drag savings relative to the supercritical airfoil at cruise conditions representative of single-aisle, transonic transport configurations. While improvements in pressure drag may be possible with variations in the relative loading between the two airfoil elements, it would be difficult to do so based on the observation that the airfoil shock is already relatively weak for a sectional lift coefficient requirement of 0.756. In order to leverage the increased aft loading of the cruise slotted airfoil, reductions in skin-friction drag are necessary to enable any potential performance improvements. The following subsection investigates the potential of the candidate cruise slotted airfoil design for supporting natural laminar flow as a means of eliminating the skin-friction penalty relative to supercritical airfoils.

C. Laminar Flow Characterization

The primary mechanisms for boundary layer transition include Görtler vortices, attachment line contamination, and modal instabilities. Görtler vortices cause boundary layer instability in regions of laminar flow where the surface curvature is negative, i.e., concave [17]. For the cruise slotted airfoil design, the main element lower surface does have significant concavity near the slot entrance; however, the primary consideration for NLF is the flap element due to its notable skin-friction drag penalty. The flap is not characterized by significant surface concavity as it produces lift primarily due to deflection without the need for aft camber. For this reason, Görtler instabilities are not expected to be a critical mechanism for estimating boundary layer transition for the cruise slotted airfoil. Similarly, attachment-line contamination is not a relevant transition mechanism for the cruise slotted airfoil, as this instability occurs in wing design when the turbulent boundary layer on the fuselage can propagate to the leading edge on a swept wing and cause transition [2]. The final transition mechanism, modal instabilities, are typically decomposed into Crossflow (CF) and Tollmien-Schlichting (TS) instabilities. CF is not considered in the present research as it is a particular concern only for swept wing design. TS is a streamwise instability mechanism due to convective traveling waves within the boundary layer. TS growth can be suppressed by providing more favorable pressure gradients over a given lifting surface [2]. For the cruise slotted airfoil assessment, TS was the only boundary layer mechanism considered to be critical for the initial assessment of laminar flow capabilities. A flight-relevant critical N-factor value of 9 was used in the present work to estimate the chordwise extent of laminar flow supported by the cruise slotted airfoil in consideration of TS growth. Transition predictions were generated using the BLSTA3D/LASTRAC software as documented in Section II.

Figure 17 shows the transition location predictions from BLSTA3D/LASTRAC for each element and surface for the slotted airfoil based on the fully turbulent pressure distributions at the 2D cruise condition ($M = 0.739$, $Re = 12.7 \times 10^6$, $c_l = 0.756$). The TS N-factor growth for each element can be explained by observing the pressure gradient behavior shown in Fig. 16. The main element upper surface shows steady TS growth from approximately $x/c_{main} = 0.05$ to 0.5, where x/c_{main} is a nondimensional chordwise distance normalized by main element chord, due the adverse pressure gradient of the supersonic rooftop. The main element lower surface shows TS growth beginning from $x/c_{main} = 0.3$ to 0.7. The TS growth in the first 30% is suppressed due to a strong favorable pressure gradient but begins to rapidly increase due to the adverse pressure gradient leading up to the beginning of the slot. The flap element lower surface shows relatively mild TS growth from $x/c_{flap} = 0.05$ to 0.6, where x/c_{flap} is the nondimensional chordwise distance normalized by flap chord, with the predicted laminar flow extent ending due to an adverse pressure gradient. For the upper surface of the flap, TS grows rather mildly from $x/c_{flap} = 0.05$ to 0.7 before terminating at the beginning of the aft pressure recovery region. A significant extent of NLF is supported on the flap upper surface due to the mitigation of any adverse pressure gradients in designing for a constant Mach number of 0.95 to maximize the lift contribution of the flap.

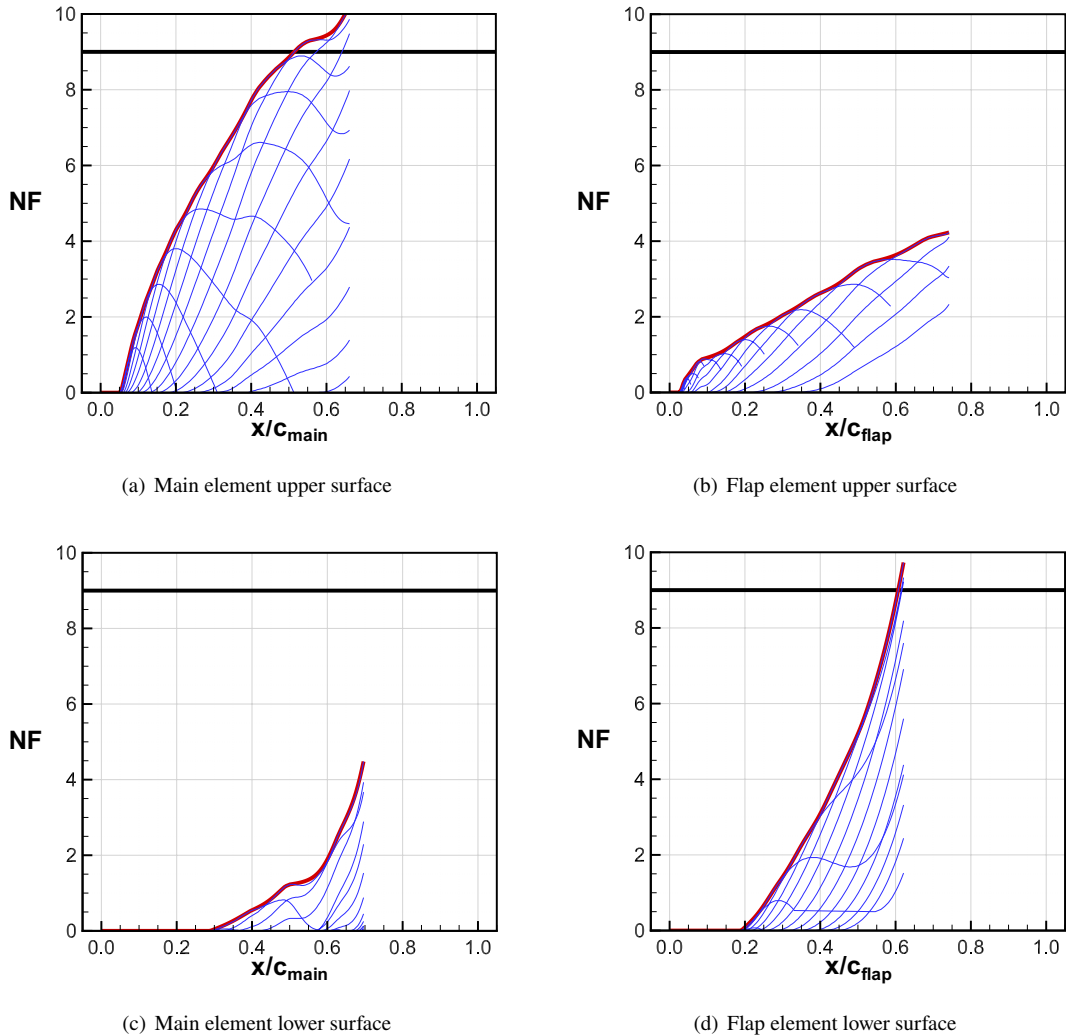


Figure 17. BLSTA3D/LASTRAC estimated transition location results for the fully turbulent cruise slotted airfoil design. TS NF growth is shown for the (a,c) main element and (b,d) flap for both the (a,b) upper and (c,d) lower surfaces.

The previous transition predictions suggest that both the main element and flap, in particular, could easily support significant extents of natural laminar flow at the current cruise condition. While it would be feasible to develop a cruise slotted airfoil with laminar flow on both elements, laminarization of only the flap presents unique NLF benefits. By limiting NLF to the flap element, there are reduced requirements for manufacturability and maintainability compared to single or multielement NLF airfoils. This also allows for the use of conventional high-lift, leading-edge devices on the main element without concerns for surface imperfections. Any benefits of the ALMA concept are likely to extend to the wing design for single-aisle, transonic transport aircraft as crossflow instability control would be less challenging due to the relatively low sweep and Reynolds numbers of the flap element. Additionally, a partially-laminarized airfoil may provide an incremental step toward integration of NLF technology on commercial transport wings. The following section introduces a cruise slotted airfoil concept with a laminarized flap to mitigate the skin-friction penalty historically associated with transonic cruise slotted airfoils.

V. Aft-Laminar Multielement Airfoil Concept

The Aft-Laminar Multielement (ALMA) concept is proposed as a transonic cruise slotted airfoil design that can overcome the skin-friction penalty associated with the flap element and provide aerodynamic performance benefits relative to conventional supercritical airfoils. The following section provides a review of the USM3D predictions for cruise, near-cruise, and low-speed performance of an initial ALMA design relative to the fully turbulent conventional and slotted airfoil designs presented in Section IV.B.

A. Cruise Performance

The forced laminarization simulation capability within USM3D was used to model the predicted extents of laminar flow on the upper and lower surface of the flap element as determined by the transition prediction analysis in Section IV.C. In this type of analysis, USM3D uses the standard SA turbulence model for the main element boundary layer and aft of the estimated transition front on the flap. Ahead of the transition front, turbulence modeling terms are suppressed to correctly model laminar flow features, such as reduced boundary layer thickness and skin-friction drag.

Figure 18 shows the USM3D pressure and skin-friction distributions for the fully turbulent conventional and slotted airfoil designs, in addition to the forced laminarization results for the ALMA concept. Relative to the fully turbulent cruise slotted airfoil, ALMA shows a more favorable pressure gradient along the upper surface of the flap. This change in flap loading can be attributed to a thinning of the boundary layer ahead of the transition front, which results in an effective change in flap camber. Because the flap loading increases when laminarizing the flap, the required lift contribution from the main element decreases to match the total cruise sectional lift coefficient. A decrease in airfoil angle of attack is then needed to reduce the main element loading, which is shown by a decrease in peak flow acceleration near the leading edge of the airfoil. The skin-friction distributions confirm that the USM3D forced laminarization feature is effectively modeling laminar flow on the flap with transition occurring near $x/c = 0.9$ and 0.95 on the lower and upper surfaces, respectively. Relative to the conventional supercritical airfoil, ALMA shows decreased skin-friction in the region from $x/c = 0.7$ to 0.95 while providing the desired increase in aft loading without boundary layer separation.

Table 5 summarizes the aerodynamic performance for the ALMA concept and fully turbulent conventional and slotted airfoil designs at cruise. With the increased aft loading enabled by the cruise slotted airfoil, the pitching moment for the fully turbulent and ALMA designs led to an 18% and 21% increase in quarter-chord pitching moment magnitude. This increase in aft loading allows for reductions in both the main element lift contribution and total airfoil angle of attack required to meet the cruise sectional lift coefficient. Laminarizing the flap element for the ALMA concept led to a 10-count reduction in sectional drag relative to the fully turbulent cruise slotted airfoil design and a 3-count or 2.7% reduction relative to the conventional supercritical airfoil. The drag savings enabled by ALMA were achieved with minimal NLF design considerations and further motivates the potential use of cruise slotted wings on single-aisle, transonic transport aircraft. It is important to note that the current ALMA design represents an initial concept developed as a product of the design exploration study and additional aerodynamic improvements might be achieved in future iterations. For example, the shock strength for the conventional airfoil was relatively weak for the current 2D cruise conditions and left little room for wave drag reduction. In the case of a higher sectional lift coefficient and/or higher Mach number, the increased aft-loading enabled by ALMA may lead to an increase in drag savings, measured by percentage, relative to fully turbulent supercritical airfoils.

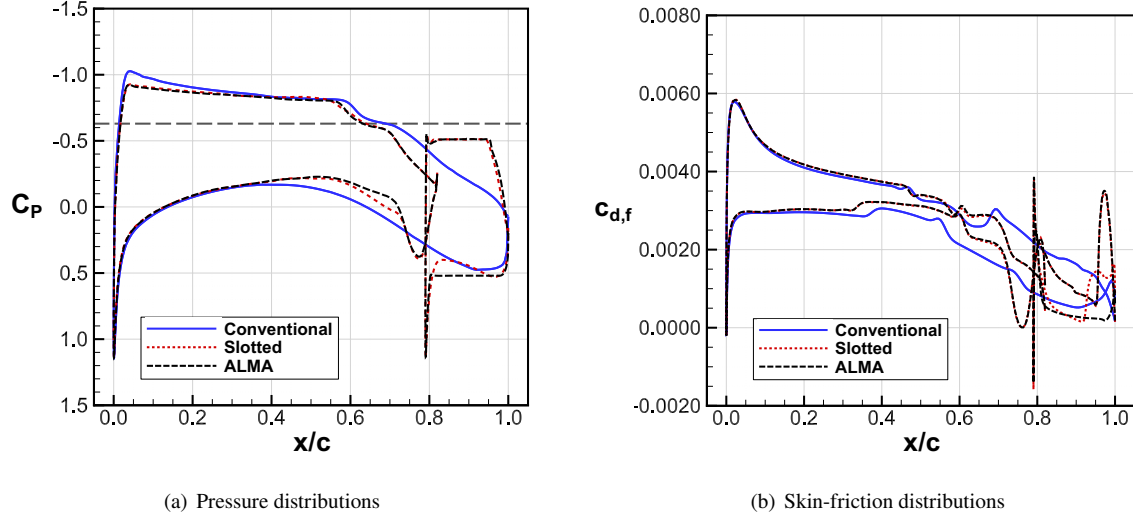


Figure 18. USM3D (a) pressure and (b) skin-friction distributions for the ALMA concept (black) and fully turbulent conventional (blue) and slotted (red) airfoils at the 2D cruise condition ($M_\infty = 0.739$, $Re = 12.7 \times 10^6$).

Table 5. Cruise aerodynamic performance for ALMA and the fully turbulent conventional and slotted airfoils.

Airfoil	Variant	c_l	c_d	$c_{d,p}$	$c_{d,f}$	c_m	α
Conventional	Turbulent Design	0.756	0.0112	0.0053	0.0059	-0.154	0.98°
Slotted	Turbulent Design	0.756	0.0119	0.0050	0.0069	-0.182	1.63°
Slotted	ALMA Design	0.756	0.0109	0.0048	0.0061	-0.187	1.52°

B. Near-Cruise Performance

In addition to evaluating the relative performance between the conventional airfoil and ALMA at cruise, a near-cruise analysis was conducted to understand how small perturbations in angle of attack and Mach number affect the predicted extents of laminar flow and aerodynamic performance. Figure 19(a) shows the drag polar and Fig. 19(b) shows the drag rise analyses for the conventional (blue), slotted (red), and ALMA (black) airfoil designs. The drag polar was calculated across an approximate angle-of-attack range of 4° in increments of 0.25° . The design lift coefficient is designated by a short dashed line with two long dashed lines representing the $\pm 10\%$ bounds. The ALMA polar data were obtained by performing stability analyses using the turbulent slotted airfoil pressure distributions and using the predicted transition fronts for USM3D forced laminarization simulations. The polar shows that ALMA has a sustained performance benefit relative to the conventional airfoil throughout the range analyzed. Additionally, both ALMA and the turbulent slotted airfoil have a more gradual increase in sectional drag at higher lift coefficient values compared to the conventional airfoil.

The drag rise plot shows the variation in total sectional drag for a Mach number range of 0.65 to 0.78. At each Mach number, the angle of attack was iteratively changed until convergence was achieved at the cruise sectional lift coefficient. For the ALMA drag rise predictions, stability analyses were performed using the fully turbulent slotted airfoil pressure distributions to estimate the transition locations for the forced laminarization simulations. For Mach numbers ranging from 0.65 to 0.74, each airfoil maintains a nearly constant sectional drag value with the ALMA design providing approximately a 2.7% drag reduction relative to the conventional airfoil. At higher Mach numbers, the cruise slotted airfoil designs show a slightly more gradual drag rise.

Figure 20 shows the USM3D pressure distributions for the (a) conventional and (b) ALMA airfoil designs at various points from the drag polar analyses. Three pressure distributions are plotted that reflect the aerodynamic performance at the design lift coefficient ($c_{l,design}$) and $\pm 10\%$ bounds to reflect near-cruise performance. Both the conventional airfoil and ALMA show an increase in the upper surface rooftop pressures with an increase in lift, i.e., angle of attack, and a forward shift and strengthening of the shock at the $+10\%$ lift coefficient point. More significantly, the flap element remains insensitive to changes in angle of attack with no noticeable change in either flap loading or predicted extent of laminar flow.

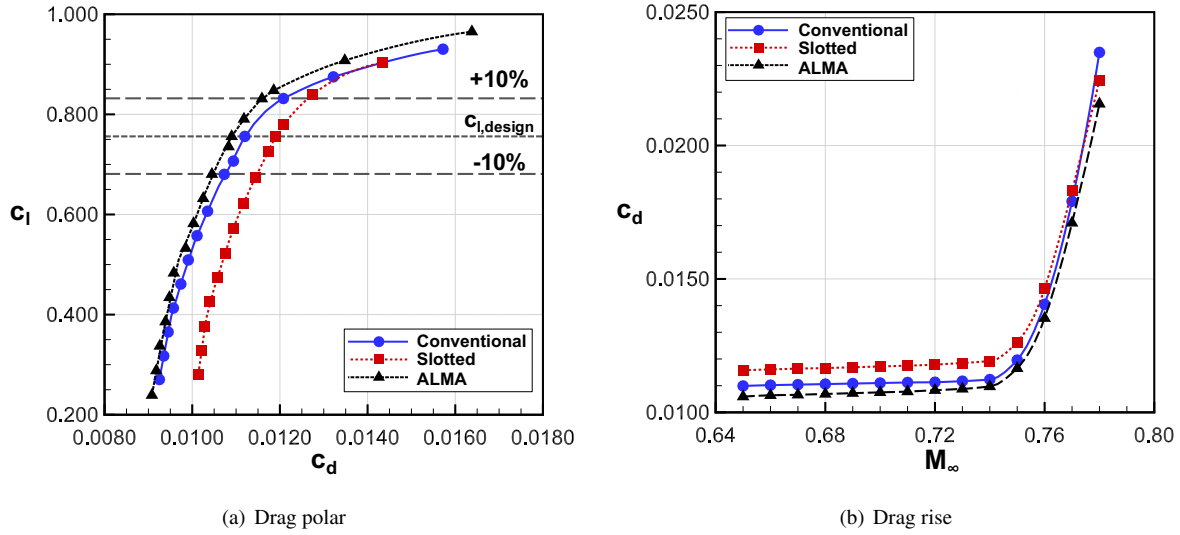


Figure 19. USM3D results for near-cruise performance of the 2D conventional (blue), slotted (red), and ALMA (black) airfoils: (a) drag polar results and (b) drag rise.

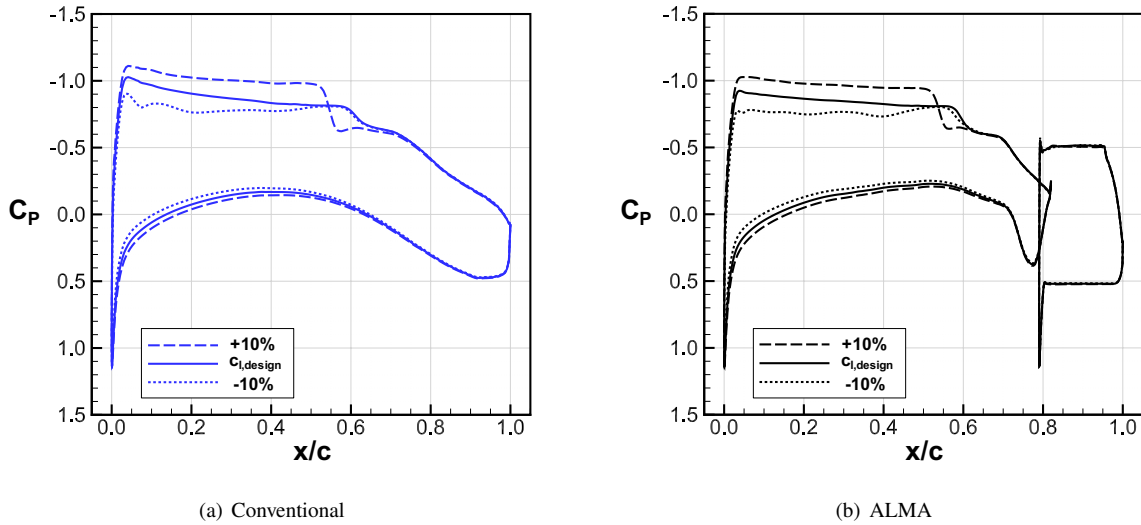


Figure 20. USM3D pressure distribution sensitivity to angle of attack for the (a) conventional and (b) ALMA airfoil designs.

Figure 21 shows the USM3D pressure distributions for the (a) conventional and (b) ALMA airfoil designs at various Mach numbers from the drag rise analyses. As Mach number increases, the shock location for the conventional airfoil gradually shifts aft in addition to strengthening up to Mach 0.77 where the flow begins to separate. Similarly, the ALMA concept shows the same trend in shock location/strength on the main element, but with a slightly higher shock strength at Mach 0.77. In terms of laminar flow extent, the flap upper surface generally remains insensitive to increases in Mach number until reaching Mach 0.77 for which the flow near the leading edge of the flap becomes slightly supersonic. This supersonic flow causes a local adverse pressure gradient; however, the TS growth remains suppressed enough to enable a negligible variation in laminar flow extent.

Ultimately, the ALMA concept shows promise as a drag-savings technology for application to transonic transport aircraft. By laminarizing the aft flap element, the skin-friction penalty resulting from the low Reynolds number boundary

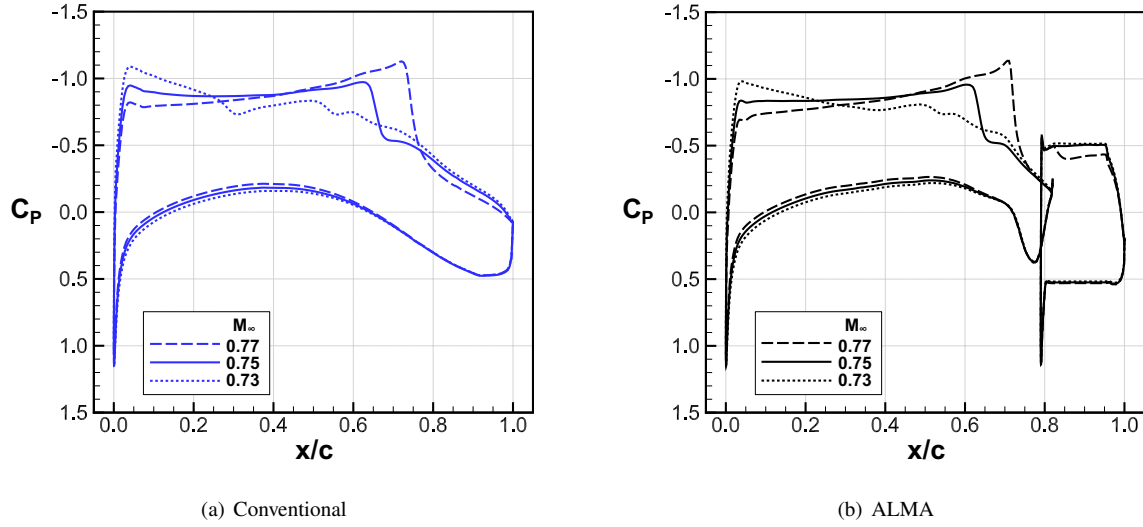


Figure 21. USM3D pressure distribution sensitivity to Mach number for the (a) conventional and (b) ALMA airfoil designs.

layer on the flap can be mitigated. Overcoming the skin-friction penalty enables the potential for wave drag reductions due to the increased aft loading of the cruise slotted airfoil that would typically lead to boundary layer separation in the case of supercritical airfoils. The near-cruise performance results showed that ALMA sustains its drag reduction with perturbations in angle of attack and Mach number while offering a more gradual drag rise. These benefits can be attributed to the negligible variation in flap loading with changes in angle of attack and Mach number, and thus, an invariable extent of laminar flow on the flap. Furthermore, the slot effect acts to limit increases in shock strength and aft translation with successive increases in angle of attack and Mach number. With favorable near-cruise performance, the following section reviews an initial assessment of the ALMA concept for low-speed, high-lift performance.

C. Low-Speed, High-Lift Performance

A low-speed, high-lift performance assessment was conducted using fully turbulent USM3D simulations at a Mach number of 0.225 and Reynolds number of 14.4 million, takeoff conditions representative of current single-aisle transport configurations. In addition to the cruise configuration, a takeoff configuration was developed through the manipulation of leading- and trailing-edge devices using CDISC. Within the CDISC module, two primary constraints, VCFLAP and MEFLAP, were developed based on the parameterization shown in Fig. 22. VCFLAP represents the variable-camber, leading-edge flap constraint, and was used to set the leading-edge deflection angle and hinge line. MEFLAP is the multielement, trailing-edge flap constraint and was used to set the flap deflection.

A baseline ALMA analysis at takeoff conditions showed that the flow reaches supersonic velocities near the leading-edge of the main element. The supersonic velocities often led to separation and a degradation in lift. The variable-camber leading edge constraint was developed as a device that could provide a more gradual flow acceleration around the leading edge to delay separation. The results of a parametric design exploration led to the leading-edge deflection rule given by Eq. 1. The leading-edge deflection, δ_{LE} , is calculated as a scaled multiple of the pressure coefficient at the leading-edge hinge line, $C_{P,h}$, and halfway along the hinge line, $C_{P,h/2}$. The design rule was implemented within CDISC as an iterative flow constraint that resulted in lower peak flow velocities at the leading edge and a more broad pressure distribution without flow separation. Equation 2 lists the hinge line best practice incorporated into CDISC based on the parametric study results. In contrast to deflection, the hinge line rule is a geometry constraint based on a scaled multiple of the leading-edge radius, $(r/c)_{LE}$. When combined with the deflection rule, the hinge line rule resulted in smoother pressure distributions with weaker adverse pressure gradients, effectively decreasing the chance of separation. Finally, the trailing-edge flap deflection was increased until encountering flow separation at approximately $x/c = 0.95$, as this provided the largest increase in sectional lift contribution for the flap. Alternative leading-edge devices and variations in flap overhang/gap were not considered and remain topics for future research.

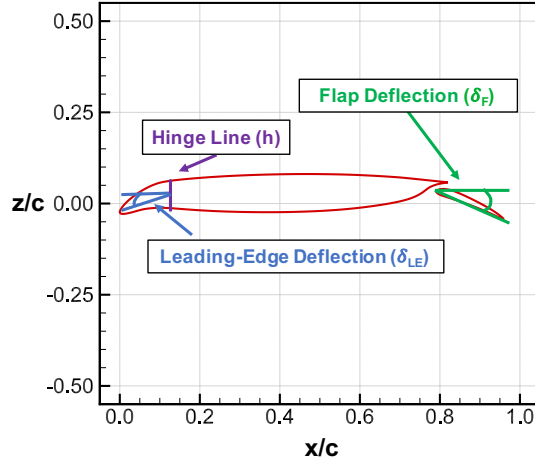


Figure 22. Parameterization of CDISC design variables for leading- and trailing-edge devices.

$$\delta_{LE} = 5(C_{P,h} * C_{P,h/2})^{0.5} \quad (1)$$

$$h = 15(r/c)_{LE} \quad (2)$$

Figure 23 illustrates the USM3D lift curve results for the ALMA airfoil in its cruise and takeoff configurations at the low-speed, high-lift condition ($M = 0.225$, $Re = 14.4 \times 10^6$). The cruise configuration was analyzed from an angle of attack range of 0 to 13 degrees, after which stall was observed. The takeoff configuration had a fixed flap deflection of 25 degrees but leveraged CDISC for leading-edge flap scheduling. As a result, the leading-edge deflection was iteratively changed at each angle of attack to minimize flow separation. The drag polar results show that the cruise configuration reaches a maximum lift coefficient of approximately 1.64 at an angle of attack of 12 degrees. For the takeoff configuration, use of the leading- and trailing-edge devices resulted in a 54% increase in maximum lift coefficient to a value of 2.53.

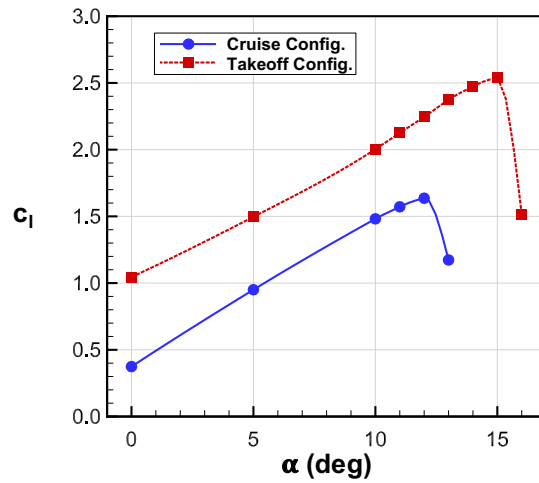
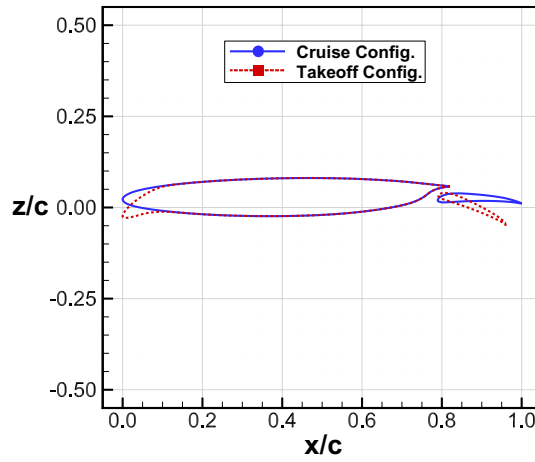
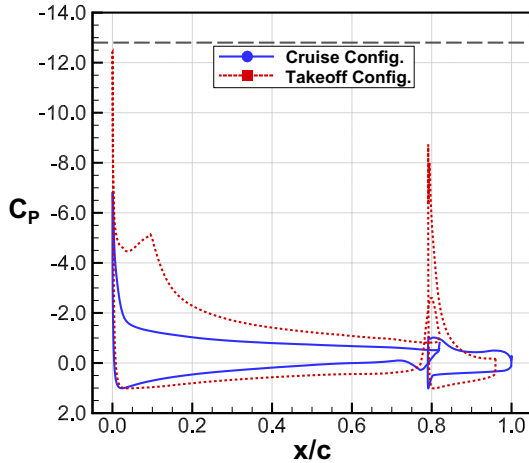


Figure 23. USM3D lift curve results for low-speed, high-lift performance of the ALMA airfoil in its cruise (blue) and takeoff (red) configuration ($M_\infty = 0.225$, $Re = 14.4 \times 10^6$).

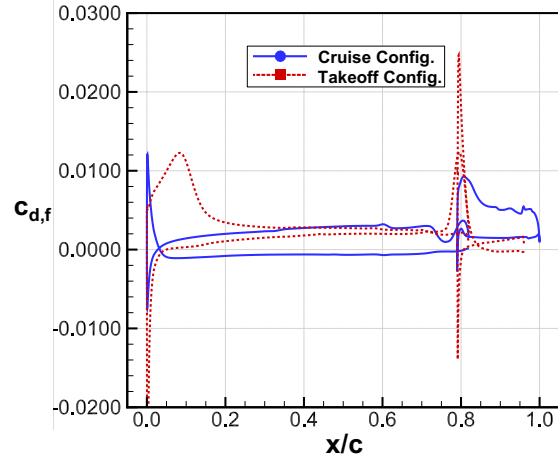
Figure 24 shows the airfoil geometry for the ALMA concept in its cruise and takeoff configurations, in addition to the fully turbulent USM3D results for the pressure and skin-friction distributions at 13 degrees angle of attack. The airfoil geometries show the difference between the cruise and takeoff configurations with a noticeable leading-edge deflection about the design hinge location and a flap deflection of 25 degrees. At this angle of attack, the cruise airfoil is well within the stall region, whereas the takeoff configuration is nearing its maximum lift coefficient. The cruise configuration is characterized by a strong peak acceleration that leads to flow separation at $x/c = 0.05$ as evident by a negative skin-friction drag value and approximately zero pressure gradient along the upper surface of the main element. While the takeoff configuration does have a weakly supersonic peak acceleration near the leading edge, the variable-camber high-lift device allows for a more gradual pressure recovery and an increase in sectional lift contribution from the main element without flow separation. Additionally, the increased trailing-edge flap deflection leads to a significant increase in aft loading with a slight separation over the last 6% of the flap chord. In conclusion, the incorporation of leading and trailing-edge devices in the low-speed, high-lift assessment of the ALMA concept supports a theoretical maximum lift coefficient of 2.5 at representative takeoff conditions. Since ALMA has a fully turbulent main element, conventional high-lift devices such as a leading-edge slat can also be investigated in future investigations.



(a) Airfoil geometries



(b) Pressure distributions



(c) Skin-friction distributions

Figure 24. USM3D results for ALMA in its cruise and takeoff configurations: (a) airfoil geometries, (b) pressure distributions, and (c) skin-friction distributions ($M_\infty = 0.225$, $Re = 14.4 \times 10^6$, $\alpha = 13^\circ$).

VI. Conclusions

The cruise slotted airfoil is a technology that has the potential to significantly improve the aerodynamic performance of commercial aircraft. The present research sought to explore and quantify the drag-saving benefits of the concept at flight conditions representative of single-aisle, transonic transport configurations using computational predictions from the USM3D flow solver. The CDISC design module was used to perform a parametric design exploration study leading to the development of best practices for transonic cruise slotted airfoil design. In the analysis process, the historically-noted skin-friction penalty of cruise slotted airfoils was found to be attributed to the introduction of a new, low-Reynolds-number boundary layer on the flap element. A comparison between conventional and cruise slotted airfoils, designed using CDISC, showed that the skin-friction penalty of the flap was large enough to offset any decreases in pressure drag provided by the slot-enabled increase in aft loading.

An Aft-Laminar Multielement Airfoil concept was proposed in which the flap element was laminarized to decrease skin-friction drag, enabling an overall reduction in sectional drag relative to modern supercritical airfoils. Using only curvature constraints to limit TS growth, a redesigned flap element was predicted to support laminar flow extents of up to 75% and 100% on the upper and lower surfaces, respectively. Forced laminarization simulations at cruise conditions showed that ALMA was predicted to decrease sectional drag by 2.7% relative to the fully turbulent supercritical airfoil. It is important to note that at the current cruise conditions, the shock strength for the conventional airfoil design was relatively low with a normal Mach number of 1.09, reducing the potential for pressure drag savings enabled by the greater aft loading of the slotted airfoil. Near-cruise analyses showed that the laminar flow extent on the flap remained constant with perturbations in angle of attack and Mach number. The ALMA concept showed a sustained increase in aerodynamic efficiency over a wide range of lift coefficients and an ability to delay the drag rise Mach number. An initial low-speed, high-lift analysis at representative takeoff conditions showed that ALMA could reach a maximum lift coefficient of 2.5 through the use of a variable-camber leading-edge device in combination with simple flap element deflection.

The computationally-predicted benefits for the initial ALMA concept warrants additional research for design refinement and future consideration of an aft-laminar cruise slotted wing design. A cruise slotted wing with a laminarized flap could serve as an incremental step toward the application of NLF technology on transonic commercial aircraft. By limiting NLF to the smaller flap element, there would be reduced requirements for manufacturability and maintainability compared to single-element NLF airfoils. By retaining a fully turbulent main element, traditional high-lift leading-edge devices may be used without concern for surface imperfections that would lead to early boundary layer transition. The predicted NLF benefits of the ALMA concept are likely to extend to wing design, as managing crossflow instabilities would be generally less challenging due to the relatively low sweep and Reynolds number of the flap. Future research is aimed at quantifying the ALMA drag-saving benefits in a 3D wing design, exploring the performance of conventional high-lift, leading-edge devices, such as a slat, and consideration of alternative design benefits, such as increased thickness, cruise Mach number, etc.

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References

- [1] Bezos-O'Connor, G., Mangelsdorf, M., Nickol, C., Maliska, H., Washburn, A., and Wahls, R., "Fuel Efficiencies through Airframe Improvements," AIAA Paper 2011-3530, June 2011. <https://doi.org/10.2514/6.2011-3530>.
- [2] Joslin, R. D., "Overview of Laminar Flow Control," NASA/TP-1998-208705, October 1998.
- [3] Wahls, R., "High Speed Slotted Wing Technology," *NASA Vehicle Systems Program Annual Meeting*, 2004.
- [4] Whitcomb, R. T., and Clark, L. R., "An Airfoil Shape for Efficient Flight at Supercritical Mach Numbers," NASA/TM-X-1109, July 1965.
- [5] Whitcomb, R. T., "Review of NASA Supercritical Airfoils," 9th International Council of the Aeronautical Sciences Congress, August 1974.
- [6] Harris, C. D., "NASA Supercritical Airfoils: A Matrix of Family-Related Airfoils," NASA/TP-1990-2969, March 1990.
- [7] McLean, J. D., Witkowski, D. P., and Campbell, R. L., "Slotted Aircraft Wing," U.S. Patent No. 7,048,235, May 2006.
- [8] Vassberg, J. C., Gea, L.-M., McLean, J. D., Witowski, D. P., Krist, S. E., and Campbell, R. L., "Slotted Aircraft Wing," U.S. Patent No. 7,048,228, May 2006.
- [9] Frink, N. T., Pirzadeh, S. Z., Parikh, P. C., Pandya, M. J., and Bhat, M., "The NASA Tetrahedral Unstructured Software System (TetrUSS)," *The Aeronautical Journal*, Vol. 104, No. 1040, 2000, pp. 491–499.
- [10] Campbell, R., "Efficient Viscous Design of Realistic Aircraft Configurations," AIAA Paper 1998-2539, June 1998. <https://doi.org/10.2514/6.1998-2539>.
- [11] Lynde, M. N., and Campbell, R. L., "Computational Design and Analysis of a Transonic Natural Laminar Flow Wing for a Wind Tunnel Model," AIAA Paper 2017-3058, June 2017. <https://doi.org/10.2514/6.2017-3058>.
- [12] Campbell, R. L., and Lynde, M. N., "A Knowledge-Based Optimization Method for Aerodynamic Design," AIAA Paper 2019-1207, January 2019. <https://doi.org/10.2514/6.2019-1207>.
- [13] Wie, Y.-S., "BLSTA: A Boundary Layer Code for Stability Analysis," NASA/CR-1992-4481, December 1992.
- [14] Chang, C.-L., "The Langley Stability and Transition Analysis Codes (LASTRAC): LST, Linear & Nonlinear PSE for 2D, Axisymmetric, and Infinite Swept Wing Boundary Layers," AIAA Paper 2003-974, January 2003. <https://doi.org/10.2514/6.2003-974>.
- [15] Kelley-Wickemeyer, R. H., Seidel, G. E., Anast, P. Z., and McLean, J. D., "Airplane with Unswept Slotted Cruise Wing Airfoil," U.S. Patent No. 6,293,497, September 2001.
- [16] Vassberg, J. C., DeHaan, M. A., Rivers, M. S., and Wahls, R. A., "Retrospective on the Common Research Model for Computational Fluid Dynamics Validation Studies," *Journal of Aircraft*, Vol. 55, No. 4, 2018, pp. 1325–1337. <https://doi.org/10.2514/1.C034906>.
- [17] Gortler, H., "On the Three-Dimensional Instability of Laminar Boundary Layers on Concave Walls," 1954.