

Aerodynamic Design Optimization of a Cruise-Slotted Transonic Truss-Braced Wing for Turbulent Flow

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This paper investigates the aerodynamic design and performance of a cruise-slotted transonic truss-braced wing (TTBW) aircraft configuration through the application of aerodynamic shape optimization based on the Reynolds-averaged Navier-Stokes equations. The TTBW and cruise-slotted wing are two advanced air transport technologies that can significantly improve aerodynamic efficiency, primarily through a reduction in induced drag, and the mitigation of shock formation and boundary layer separation, respectively. However, it remains to be seen whether these technologies can be combined while retaining the individual benefits. To address this question, aerodynamic shape optimization is applied to the wing and strut of a wing-strut-fuselage geometry of the cruise-slotted TTBW configuration, as well as a non-slotted TTBW serving as a reference aircraft. Results indicate that aerodynamic shape optimization is successful in achieving an aerodynamically efficient cruise-slotted TTBW design for fully turbulent flow, with similar features to those of the optimized non-slotted TTBW. With regard to aerodynamic performance, the optimized cruise-slotted TTBW experiences more drag at Mach 0.800 than the non-slotted variant, but has the advantage of a more gradual drag rise as the operating Mach number is increased. This was found to be the case even when optimizing the two configurations for higher design Mach numbers. However, the low wave drag of both sets of optimized designs mitigates the airfoil technology factor advantage of the cruise-slotted wing, resulting in lower maximum aerodynamic range efficiency.

Nomenclature

α	=	Angle of attack
D	=	Drag
C_D	=	Drag coefficient
C_L	=	Lift coefficient
C_P	=	Pressure coefficient
C_{geo}	=	Geometric equality constraints
$\mathcal{G}_{\text{geo}}$	=	Geometric inequality constraints
L	=	Lift
L/D	=	Lift-to-drag ratio
M	=	Mach number
$\mathbf{x}$	=	Design variables
x, y, z	=	Cartesian coordinates
y^+	=	Nondimensional off-wall distance

Acronyms

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FFD	=	Free-Form Deformation
LAVA	=	Launch, Ascent, and Vehicle Aerodynamics
LE	=	Leading Edge
MFW	=	Maximum Fuel Weight
MTOW	=	Maximum Takeoff Weight
MZFW	=	Maximum Zero Fuel Weight
OEW	=	Operating Empty Weight
RANS	=	Reynolds-Averaged Navier-Stokes
SA	=	Spalart-Allmaras
SNOPT	=	Sparse Nonlinear Optimizer
SOC	=	Start of Cruise
TE	=	Trailing Edge
TTBW	=	Transonic Truss-Braced Wing
TTBW-150	=	Single-Aisle Transonic Truss-Braced Wing
TTBW-CS-150	=	Single-Aisle Cruise-Slotted Transonic Truss-Braced Wing

I. Introduction

According to the Aviation Climate Action Plan released by the United States in 2021, the U.S. aviation sector is projected to double its CO₂ emissions per year by 2050 if no further action is taken due to the steady growth in the demand for aviation [1]. NASA’s response is the Aeronautics Research Mission Directorate (ARMD) Strategic Implementation Plan, where one of the main strategic thrusts is to achieve ultra-efficient subsonic transport by accelerating performance improvements in drag, weight, and propulsion to reduce aviation energy consumption and environmental impact [2]. With regard to improvements in drag, two advanced air transport technologies that can potentially contribute significantly are the transonic truss-braced wing (TTBW) aircraft configuration and the cruise-slotted wing.

The TTBW [3] is an unconventional aircraft configuration that has the main advantage of a much larger wing span, typically 25-50% greater than that of an equivalent conventional tube-and-wing aircraft. This significantly reduces induced drag, improving aerodynamic efficiency and hence energy efficiency. To support the increased wing-bending loads that come from such a large wing span, the wing is structurally braced by a main strut, with the option of one or more jury struts. Further, the structural efficiency of the truss-braced wing topology can also be leveraged for other design trades, for example, for reductions in wing weight, reductions in wing thickness-to-chord ratio, and reductions in wing sweep. Reducing wing sweep can also reduce wing weight, which can be further traded for thinner wings to counteract any penalties in wave drag. This can enhance opportunities for introducing natural-laminar-flow wing technology by combining reduced cross-flow instabilities with the already low Reynolds numbers of the TTBW configuration. Some examples of major efforts focused on the TTBW concept include Boeing’s Mach 0.70 SUGAR High [4] and SUGAR Volt [5], as well as Boeing’s Mach 0.745 [6] and Mach 0.80 [7, 8] TTBW vision vehicles. Until recently, Boeing was focused on the Mach 0.80 variant and had been engaged with NASA to develop the Sustainable Flight Demonstrator, or X-66 [9], a research aircraft under NASA ARMD’s Sustainable Flight National Partnership [10]. However, this effort was paused to concentrate near-term efforts on thin wing technology [?].

The cruise-slotted wing is another advanced air transport technology, originally proposed by Whitcomb and Clark in 1965 [11] to improve transonic aerodynamic performance. This wing configuration features a multi-element or slotted airfoil, as shown in Figure 1, where airflow through the slot allows for an increase in aerodynamic loading over the main element without boundary layer separation. Overall, this can enable a wing design with increased loading, featuring a very strong pressure recovery over the main and aft elements. The slotted airfoil can also enable operation at higher Mach numbers given its ability to mitigate boundary layer separation that can be encountered with shock formation, i.e. shock-induced boundary layer separation, on the main element [11]. Conceptually, this translates to higher airfoil technology factors, which reduce compressibility drag through the Korn equation [12]. Indeed, Boeing suggests that a properly designed cruise-slotted wing can allow transport aircraft to operate at increased cruise Mach numbers for a similar maximum aerodynamic range efficiency, i.e. $M(L/D)$, where M is the Mach number and L/D is the lift-to-drag ratio [13]. This is shown in Figure 2 where cruise at an increased Mach number is traded for a small penalty in the maximum $M(L/D)$. These results were obtained from wind tunnel tests comparing a partial-span slotted wing configuration—including the wing, fuselage, horizontal and vertical tails, nacelles, and pylons—with an equivalent conventional wing configuration that accounts for system-level changes [13].

The gradual pressure recoveries over the main and aft elements can also provide opportunities for natural-laminar-flow

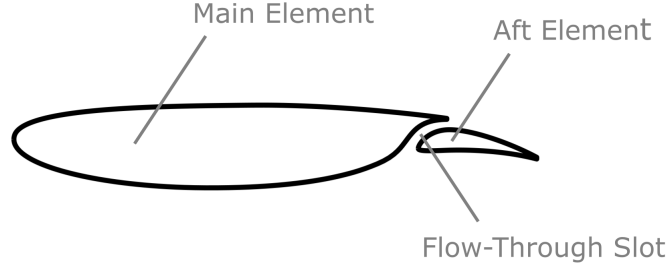


Fig. 1 Notional slotted airfoil profile.

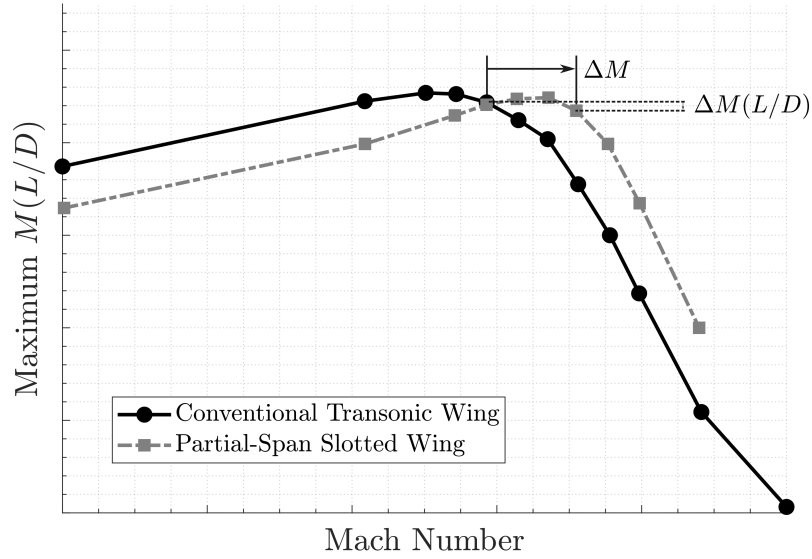


Fig. 2 Wind tunnel data illustrating the potential benefits of a partial-span slotted wing, adapted from Vassberg et al. [13].

wing technology. For example, Hiller et al. [14] applied a knowledge-based aerodynamic design framework based on the Reynolds-averaged Navier-Stokes (RANS) equations to investigate the design of a transonic slotted airfoil and found that their Aft-Laminar Multielement Airfoil (ALMA) can provide a 3% drag reduction compared to an equivalent conventional transonic airfoil. Hiller et al. [15] then extended this to the design of a partially slotted wing based on a Mach 0.80 variant of the NASA Common Research Model [16]. Although a similar drag count was obtained between the cruise-slotted and conventional wing designs, a net drag benefit was achieved when considering Mach numbers exceeding the design point, resulting from the more gradual drag rise behavior of the slotted airfoils. This was found to be the case under both natural laminar flow and turbulent flow conditions. Other researchers have also investigated the design of slotted airfoils for natural laminar flow, albeit for reduced transonic Mach numbers. See for example work on the Slotted Natural Laminar Flow (SNLF) airfoil by Somers [17], and Coder and Somers [18]. This airfoil was also implemented on the wing of a Mach 0.70 TTBW and analyzed with free transition by Perkins et al. [19]. Although the truss was not included, results from these simulations suggest the potential for extended regions of laminar flow over the lower and upper surfaces of the wing.

The design of a cruise-slotted wing is not without its challenges, however. For example, one must consider the potential penalties in skin-friction drag that comes from the higher wetted area of the slotted airfoil. Moreover, Hiller et al. [14, 15] showed that the high-speed flow over the aft element also causes it to exhibit relatively high skin-friction drag coefficients that can mitigate the slotted airfoil's overall drag benefit. Several challenges at the aircraft system level must also be addressed, such as increased nose-down pitching moments from the increased wing aft loading, and the structural integration of the main and aft wing elements.

Notwithstanding these system-level challenges, a properly designed cruise-slotted wing can reduce drag relative

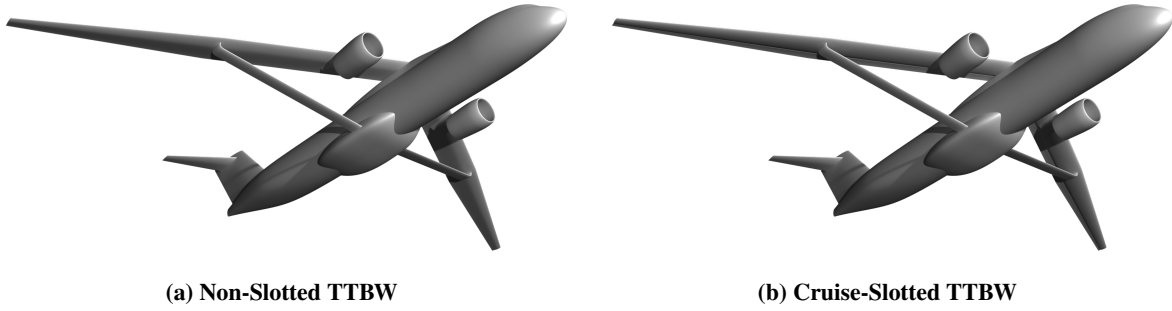


Fig. 3 Concepts of the non-slotted and cruise-slotted TTBW aircraft configurations.

to an equivalent conventional wing [14, 15], while providing the benefits of operating at higher Mach numbers for a similar aerodynamic range efficiency [13]. Therefore, the question that follows is whether the TTBW and cruise-slotted wing technologies can be combined to improve overall vehicle aerodynamic performance. The first major challenge will be addressing transonic interference effects arising from the narrow—and sometimes closed—junctions between the wing and strut(s), particularly when incorporating the cruise-slotted wing topology. For TTBWs, this can cause shock formation and boundary layer separation, which can significantly diminish the overall advantages of the configuration.

Recent advances in computational tools and capabilities for high-fidelity aerodynamic shape optimization have proven to be invaluable in this regard. For example, Secco and Martins [20] addressed the transonic interference effects of a Mach 0.72 single-aisle strut-braced wing through the application of aerodynamic shape optimization based on the RANS equations. Chau and Zingg then demonstrated that these adverse effects can also be eliminated for Mach 0.78 regional jet [21, 22] and single-aisle [23] strut-braced-wing aircraft operating at the relatively high lift coefficients required to obtain optimum aerodynamic performance. Single- and multi-point RANS-based aerodynamic shape optimization was also applied, with results from systems analysis indicating that block fuel savings on the order of 7 to 8% can be achieved in both aircraft classes relative to conventional tube-and-wing aircraft based on the E190-E2 and A320neo. Once it has been demonstrated that the transonic interference effects of the cruise-slotted TTBW can be mitigated, the question that remains is whether a net aircraft-level benefit can be achieved—either in the form of reduced cruise drag, or operation at higher cruise Mach numbers without significantly compromising aerodynamic range efficiency.

The present paper investigates the aerodynamic design and performance of the cruise-slotted TTBW configuration under fully turbulent flow through the application of aerodynamic shape optimization based on the RANS equations. Specifically, a high-sweep, Mach 0.80, single-aisle TTBW configuration with a full-span slotted wing is considered to serve as a proof of concept. The main objectives are to (i) determine whether the unique aerodynamic design challenges of the TTBW configuration can be addressed when including the slotted airfoil, and (ii) evaluate the aerodynamic performance of the cruise-slotted TTBW relative to a similarly-optimized non-slotted TTBW. Investigations of the cruise-slotted TTBW's aerodynamic performance will also consider higher Mach numbers via Mach number sensitivity studies. Figure 3 shows concepts of the two aircraft configurations considered in this work.

The paper is organized as follows. Section II presents the computational design and analysis tools and capabilities used in the present paper, including details on the high-fidelity aerodynamic shape optimization framework. Section III presents the aircraft concepts, their characteristics, and their operating conditions. Section IV then presents the aerodynamic shape optimization problems and results. Mach number sensitivity studies are included in Section V, with conclusions and future work presented in Section VI.

II. Computational Design and Analysis Tools and Capabilities

A. High-Fidelity Aerodynamic Shape Optimization Framework

The aerodynamic design of the non-slotted and cruise-slotted TTBWs is performed through the Jetstream high-fidelity aerodynamic shape optimization framework developed by the Computational Aerodynamics Lab at the University of Toronto Institute for Aerospace Studies [24]. It consists of (i) an integrated mesh parameterization and deformation method, (ii) a free-form and axial deformation geometry control system, (iii) a Newton-Krylov-Schur flow solver

for the RANS equations, (iv) the discrete-adjoint method for gradient evaluation, and (v) SNOPT for gradient-based optimization.

Components (i) and (ii) comprise a two-level geometry and mesh parameterization and deformation method [25] where a baseline grid is first parameterized with B-spline curves, surfaces, and volumes. The control points of these B-splines provide the means for mesh and hence geometry control, and form the basis of the mesh deformation scheme [26]. Although the B-spline control points that define the aerodynamic surfaces can be used to directly control the geometry, they are instead embedded within free-form deformation (FFD) volumes [27], which decouple the geometry parameterization and geometry control schemes. This allows the user to control the resolution of the geometry parameterization separately from the resolution of the geometry control system, which drives the number of optimization design variables.

In this method, the FFD volumes are defined as B-spline volumes themselves whose control points can be manipulated in x , y , and z to smoothly deform the embedded objects. However, we further reduce the number of degrees of freedom by translating the FFD-volume control point coordinates to more meaningful aerodynamic design variables as will be described in Section IV.C. As will also be described in Section IV.C, the FFD volumes are also attached to axial curves, which aid in defining the aerodynamic design variables while also allowing for additional geometric freedom. Once the B-spline control points defining the aerodynamic surfaces have been deformed by the geometry control system, the perturbations are propagated across the B-spline control grid through a linear-elasticity-based model. The deformed computational grid is then obtained by re-evaluating the parametric locations of the computational nodes on the deformed B-spline control grid.

Component (iii) provides the means for simulating aerodynamics and computing the aerodynamic functionals. This parallel implicit structured multiblock Newton-Krylov-Schur algorithm [28] is used to solve the steady-state RANS equations fully coupled with the Spalart-Allmaras (SA) [29] turbulence model. Specifically, SA-neg [30] is used with the quadratic constitutive relation, QCR2000 [31], which has been shown to aid in more accurately detecting regions of boundary layer separation [32], relevant to the design of wing-fuselage junctions and more importantly, wing-strut junctions. Since we consider only turbulent designs in the current work, boundary layers are assumed to be fully turbulent.

Spatial discretization of the RANS equations is achieved through second-order centered summation-by-parts operators with simultaneous approximation terms to weakly couple block-to-block interfaces and enforce boundary conditions [33]. A pressure-based shock sensor with scalar dissipation is also included to stabilize the flow solution around shock waves. The numerical solution is driven to steady-state via an inexact Newton method, with globalization achieved using pseudo-transient continuation. The linear system at each Newton iteration is solved using a flexible variant of the general minimum residual (GMRES) method [34, 35].

Numerical optimization is provided by components (iv) and (v), which include the gradient-based optimizer SNOPT [36] and the discrete-adjoint method [37, 38] for the computation of objective function and constraint gradients that depend on the flow solution or the mesh deformation. These provide a computationally efficient means for solving the aerodynamic design optimization problems considered in this work, which include on the order of hundreds of design variables. For all other sensitivities, gradients are calculated analytically or through the complex-step method [39].

B. The Launch, Ascent, and Vehicle Aerodynamics (LAVA) Curvilinear Flow Solver

Post-optimization grid-convergence studies are performed using the Launch, Ascent, and Vehicle Aerodynamics (LAVA) Curvilinear flow solver [40]. This flow solver is also based on the RANS equations and is similar in accuracy and efficiency to that of Jetstream. However, the LAVA framework enables the use of structured overset meshes, which was found to be advantageous for maintaining the quality and resolution of the grid in and around regions of high geometric complexity such as the slot of the cruise-slotted wing around the wing tip. These regions were found to be problematic when utilizing the automatic grid refinement capabilities within Jetstream, leading to reduced flow solver robustness when considering very fine grids. Fortunately, the flow features around these problem areas do not largely effect vehicle aerodynamic performance and were found to have minimal impact on the design optimizations. As such, the coarse but robust structured multiblock meshes used for optimization were still deemed sufficient.

The version of the LAVA Curvilinear flow solver used in the present paper is a second-order finite-difference code for the RANS equations coupled with the one-equation SA turbulence model [29]. Rotation curvature (RC) corrections [41] and QCR2000 [31] are included, resulting in the SA-RC-QCR2000 turbulence model. Boundary layers are also assumed to be fully turbulent. Convective fluxes are calculated using a modified Roe scheme implemented with third-order upwind flux reconstruction and the Koren flux limiter [42, 43]. For the turbulence model's convective terms, a first-order

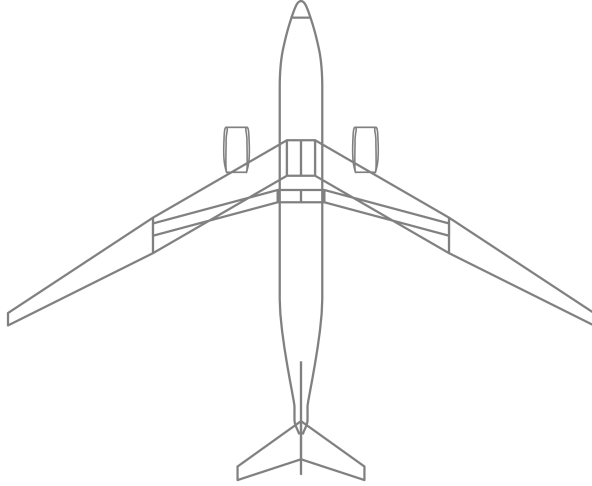


Fig. 4 Reference TTBW aircraft concept.

Table 1 Aircraft characteristics, design requirements, and operating conditions for the reference TTBW aircraft concept.

Parameter	Value
Mean aerodynamic chord (ref.), ft	9.17
Wing area (gross, ref.), ft ²	1,467
Wing span, ft	170.0
Wing aspect ratio	19.70
Wing sweep (mid chord), deg	30.0
Wing loading, lb/ft ²	110.0
Thrust-to-weight ratio	0.320
MTOW, lb	156,010
MZFW, lb	132,295
OEW, lb	86,300
MFW, lb	33,430
Maximum payload, lb	46,000
Design payload, lb	30,800
Design range, nmi	3,500
Economy range, nmi	900
Mach number (SOC, economy)	0.800
Altitude (SOC, economy), ft	43,000
Lift coefficient (SOC, economy)	0.560

upwind approach is applied. Steady-state solutions are obtained with a parallel implicit Newton-Krylov method, and uses pseudo-transient continuation for improved robustness. Each Newton step involves solving a linear system using the GMRES algorithm [44], preconditioned with incomplete LU factorization.

III. Aircraft Characteristics and Operating Conditions

The non-slotted and cruise-slotted TTBWs are developed based on a common aircraft concept, which assumes a similar overall aircraft sizing and operating envelope between the two configurations. This aircraft concept is shown in Figure 4 and is based on the high-sweep, Mach 0.800 variant of the Boeing SUGAR High from Bradley et al. [4], both in terms of its overall dimensions and its top-level aircraft requirements. This concept is a 154-passenger single-aisle transport aircraft and is developed through the application of a conceptual multidisciplinary design optimization framework [21], which has been used to develop concepts for several conventional and unconventional aircraft configurations based on first-order disciplinary trades (see for example References [21, 23, 45]). Table 1 summarizes the key characteristics, design requirements, and operating conditions for the conceptual model. This includes a design payload and range of 30,800 lb and 3,500 nmi, respectively, and an economy payload and range of 30,800 lb and 900 nmi, respectively.

For both aircraft configurations, aerodynamic shape optimization is applied at the start of cruise (SOC) conditions of the economy range mission. This mission represents a typically-flown mission and is used to define the design operating conditions, namely, cruise at Mach 0.800, an altitude of 43,000 ft, and a lift coefficient of 0.560. For the remainder of the present paper, the non-slotted and cruise-slotted TTBW configurations are herein also referred to as the TTBW-150 and TTBW-CS-150, respectively.

Table 2 Grid information for the structured multiblock grids used with the Jetstream framework for aerodynamic shape optimization.

Configuration	Grid Level	Number of Blocks	Number of Nodes	Avg. Off-Wall Spacing ¹	Avg. y^+ ²
TTBW-150	L0	898	18.25×10^6	1.45×10^{-6}	0.494
TTBW-CS-150	L0	1,406	22.65×10^6	1.42×10^{-6}	0.511

¹Off-wall spacings are in units of mean aerodynamic chord.

²Based on flow solutions at Mach 0.800.

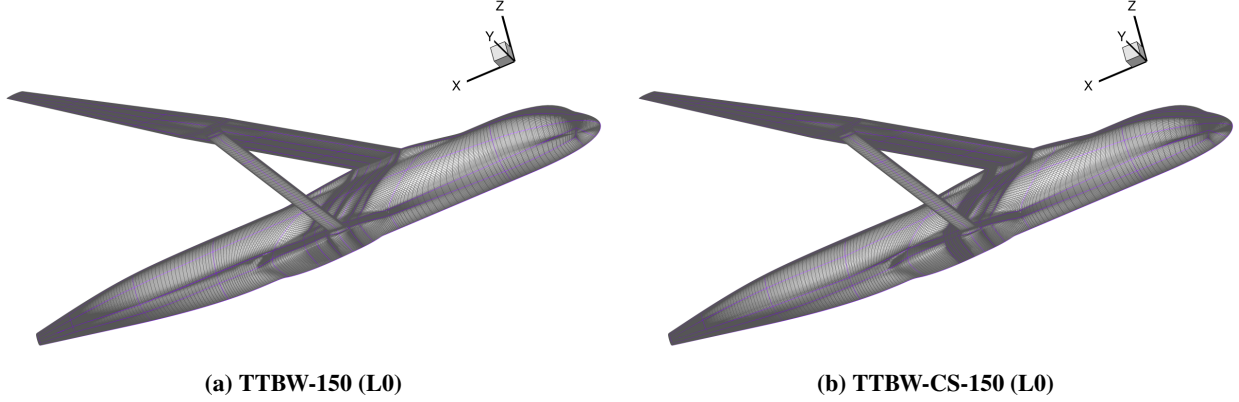


Fig. 5 Surface meshes and patch topologies of the structured multiblock grids used with the Jetstream framework for aerodynamic shape optimization.

IV. High-Fidelity Aerodynamic Shape Optimization

A. Baseline Geometries

Baseline geometries are developed for the TTBW-150 and TTBW-CS-150 configurations based on the aircraft concept presented in Section III. These models include the wing, strut, and fuselage, which are common between the two configurations except for the wing sections. For the baseline TTBW-150, the wing is defined by RAE-2822 airfoil profiles, which are reasonable starting points for transonic wing design. For the baseline TTBW-CS-150, the wing is defined by slotted airfoils based on the original profiles proposed by Whitcomb and Clark [11], but modified with an increased aft-element leading-edge (LE) radius following the designs presented in References [13, 14]. This is done to improve aerodynamic performance robustness over a range of operating conditions. As will be described in Section IV.C, the current work considers the design of the wing sections via a unified approach that views the wing sections as integrated airfoils. Therefore, such detailed modifications must be introduced *a priori*.

The fuselage geometries are based on the Boeing SUGAR High [4], while the wing and strut fairings are modeled after the open strut-braced-wing geometry from the PADRI workshop [46]. The baseline struts are defined by symmetric supercritical SC(2)-0012 airfoil profiles.

B. Computational Grids

For aerodynamic shape optimization, structured multiblock grids are developed for use with the Jetstream framework. These three-dimensional grids have O-O blocking topologies with no bi-directional boundary layer meshes, and are developed based on the gridding guidelines of the Fourth Drag Prediction Workshop (DPW) [47]. Specifically, the grids are developed based on the coarse-medium grid requirements and consist of 18.25 and 22.65 million grid nodes for the TTBW-150 and TTBW-CS-150 configurations, respectively. Table 2 provides a summary of the grid information for these coarser, optimization level grids. Note that the difference in the number of blocks is due to the higher geometric complexity of the cruise-slotted TTBW configuration. Figure 5 shows the surface meshes and patch topologies for the TTBW-150 and TTBW-CS-150 models.

Post-optimization flow analysis for computing aerodynamic performance is performed with the LAVA Curvilinear

Table 3 Grid information for the structured overset grids used with the LAVA Curvilinear flow solver for post-optimization analysis.

Grid Level	Number of Nodes	Avg. Off-Wall Spacing ¹	Avg. y^+ ²
TTBW-150			
L0	33.10×10^6	2.14×10^{-5}	0.937
L1	64.78×10^6	1.15×10^{-5}	0.684
L2	130.54×10^6	5.14×10^{-6}	0.560
TTBW-CS-150			
L0	35.67×10^6	2.08×10^{-5}	0.938
L1	69.58×10^6	1.11×10^{-5}	0.676
L2	140.33×10^6	5.01×10^{-6}	0.568

¹Off-wall spacings are in units of mean aerodynamic chord.

²Based on flow solutions at Mach 0.800.

flow solver, which uses structured overset meshes in the current work. These grids are generated for the optimized TTBW-150 and TTBW-CS-150 designs and include coarse, medium, and fine grid levels for performing grid-convergence studies. These grid families provide the means for estimating grid-converged aerodynamic functionals, enabling more direct comparisons between the two aircraft configurations, which differ in geometric complexity. Grid families are also developed for the additional optimized designs presented in Section V, which are a part of the Mach number sensitivity studies. Grid information for the grid families developed for the nominal operating conditions is included in Table 3. The corresponding surface meshes and patch topologies for each grid family are shown in Figure 6.

C. Optimization Problems

The aerodynamic design of the TTBW-150 and TTBW-CS-150 configurations are formulated as optimization problems of the form:

$$\begin{aligned}
 &\text{minimize} && C_D \\
 &\text{w.r.t.} && \mathbf{x} \\
 &\text{s.t.} && L = W, \\
 &&& C_{\text{geo}} = 0, \quad \mathcal{G}_{\text{geo}} \leq 0
 \end{aligned}$$

where C_D is the cruise drag coefficient at the design point, $\mathbf{x} = [\alpha, \mathbf{x}_{\text{geo}}^T]^T$ is the design variable vector, which includes angle of attack, α , and the vector of geometric design variables, $\mathbf{x}_{\text{geo}}$, and C_{geo} and $\mathcal{G}_{\text{geo}}$ are the geometric equality and inequality constraints, respectively.

Figure 7 shows the free-form and axial deformation geometry control systems, which define the geometric design variables. For both aircraft configurations, the B-spline control points that parameterize the wing and strut are embedded within FFD volumes, with the FFD volume control points arrayed in 2×11 cross-sections, which are used to define twist and section shape design variables. The twist design variable is defined as a rotation of a given FFD volume cross-section about the local origin, while the section shape design variables are vertical displacements along the local z -axis. The local coordinate systems are defined by the axial curves positioned at the $1/4$ -chord of the wing and strut. These axial curves are defined as B-spline curves whose control points can also be manipulated to drive the attached FFD-volume cross-sections, providing more global degrees of freedom such as sweep, span, and dihedral design variables. However, these degrees of freedom are omitted in the current work to minimize the impact of the aerodynamic design on other disciplines.

Note that the FFD-volume cross-sections are uniformly distributed in order to reduce optimization bias toward any specific area. This is with the exception of the wing root and tip, and around the wing-strut junction where additional degrees are necessary for addressing adverse effects in high gradient regions of the flow, including transonic interference effects. In the present paper, the main and aft elements of the TTBW-CS-150 configuration are also only embedded

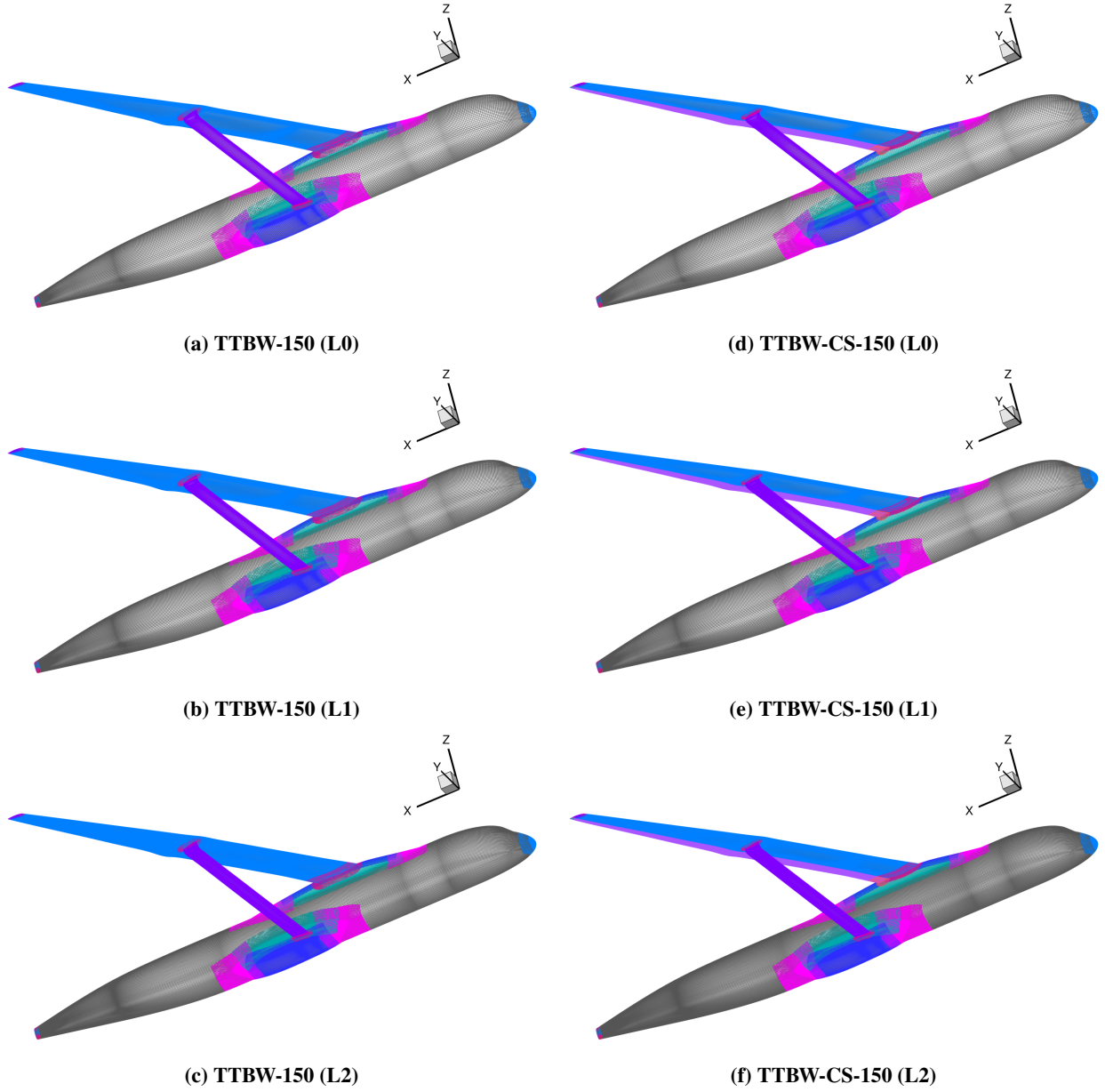


Fig. 6 Surface meshes and patch topologies of the structured overset grids used with the LAVA Curvilinear flow solver for post-optimization analysis.

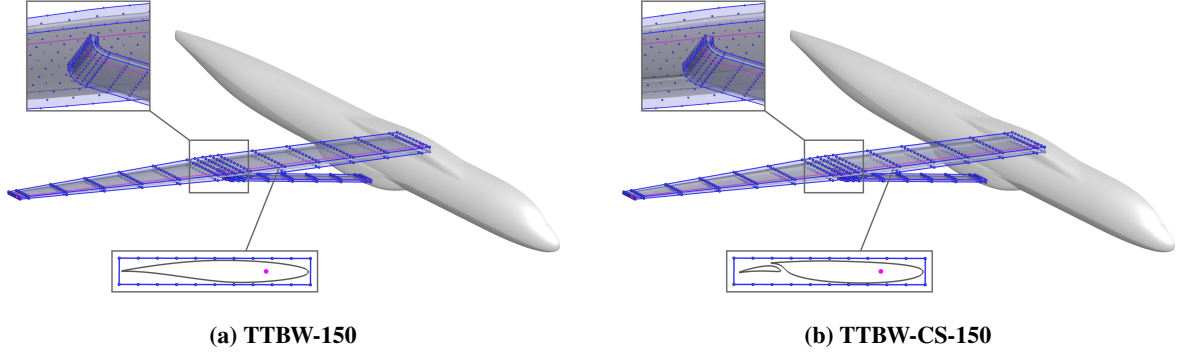


Fig. 7 Axial and free-form deformation geometry control systems for aerodynamic shape optimization with axial curves (magenta lines) and FFD volumes (blue points and surfaces).

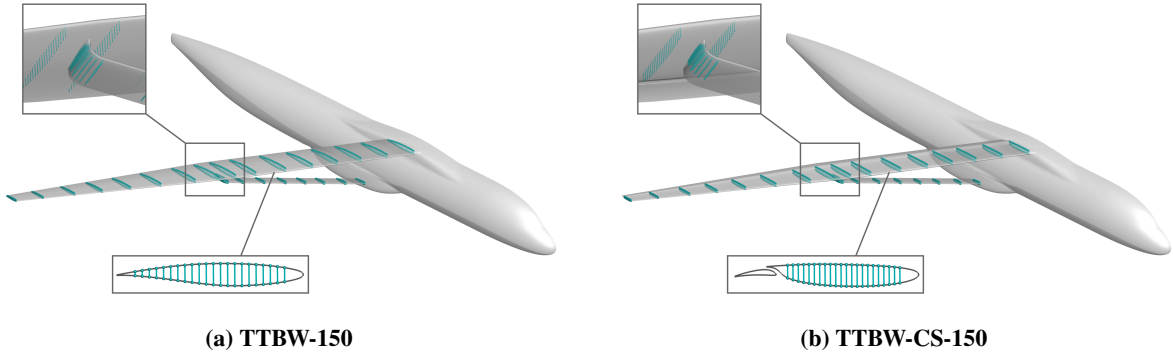


Fig. 8 Minimum $(t/c)_{\max}$ constraint probes (teal points and lines) for aerodynamic shape optimization.

within one FFD volume to reduce geometric complexity. This provides an integrated approach to design, which views the multi-element topology as a unified wing section, and is more suitable to the implicit geometry control of FFD methods.

In order to minimize drag at cruise, we include a constant lift constraint based on the weight of the aircraft. Another important consideration for cruise flight is the pitching moment of the aircraft, which can be trimmed with a zero pitching moment constraint. However, since the computational aircraft models do not include the tail systems, we opt not to include such a constraint. This reduces not only the computational cost of a given flow solution, but also reduces the computational cost of the optimization problem by not requiring an additional flow-based adjoint solution.

Geometric constraints are also included to maintain the feasibility of the aircraft concepts. This includes a minimum wing and strut volume constraint based on the volume of the fuel tanks estimated from systems analysis, as well as minimum $(t/c)_{\max}$ constraints, which aid in maintaining a minimum structural depth, also based on systems analysis. As shown in Figure 8, the minimum $(t/c)_{\max}$ constraints are enforced at 30 wing and strut sections and are calculated at each station based on the maximum of 22 thickness probes distributed along the chord. To reduce geometric complexity, linear twist constraints are also included over the strut FFD-volume cross-sections. Specifically, a linear twist interpolation is imposed on the FFD-volume cross-sections over the transition strut, and a twist linking constraint is imposed over the vertical strut. A linear twist interpolation constraint is also applied over the wing across the wing-strut junction to prevent highly local design features, which were encountered during earlier aerodynamic design optimizations.

Lastly, minimum t/c scaling and fixed LE and trailing-edge (TE) constraints are also included. The former enforces a lower and upper bound on the local vertical distance between a given pair of FFD-volume control points, while the latter prevents shear twist and translations of the wing systems. Tables 4 and 5 summarize the design variables and constraints, respectively, for the TTBW-150 and TTBW-CS-150 optimizations.

Table 4 Aerodynamic shape optimization design variables.

Design variable	Quantity	Lower bound	Upper bound
Angle of attack	1	−3.0 deg	+3.0 deg
Twist	35	−10.0 deg	+10.0 deg
Wing	17	−10.0 deg	+10.0 deg
Strut	18	−10.0 deg	+10.0 deg
Section shape	770	0.5	2.0
Wing	374	0.5	2.0
Strut	396	0.5	2.0
Total	806	— —	— —

Table 5 Aerodynamic shape optimization constraints.

Constraint	Quantity	Description
Lift	1	Constrains the aircraft lift to equal the weight at the start of cruise (nonlinear)
Minimum volume	1	Constrains the minimum wing (and strut) OML volume based on fuel storage requirements (nonlinear)
Minimum $(t/c)_{\max}$	30	Minimum maximum thickness-to-chord ratio constraints based on structural requirements (nonlinear)
Minimum t/c scaling	385	Constrains the local vertical separation between each pair of FFD-volume control points to be greater or equal to 50% of its initial value (linear)
Fixed LE/TE	70	Constrains section shape design variables at the LE and TE to be equal and opposite between the lower and upper FFD-volume control points (linear)
Linear junction wing twist	1	Interpolates the twist design variables across the 9th and 11th wing FFD-volume cross-sections (linear)
Linked vertical strut twist	1	Links the twist design variables of the vertical strut segment (linear)
Linear transition strut twist	1	Interpolates the twist design variables across the transition strut segment (linear)

D. Optimization Results

Optimization of the TTBW-150 and TTBW-CS-150 configurations completed in approximately 100 major iterations, with the objective functions converged to a tenth of a drag count and constraint violations reduced to 10^{-5} or less. Figures 9 and 10 provide overviews of the initial and optimized design and flow features for the TTBW-150 and TTBW-CS-150 configurations, respectively. From Figures 9a and 10a, it can be seen that the initial shock waves on the wing upper surface and within the wing-strut junction of both configurations have been largely eliminated. Although RANS-based aerodynamic shape optimization tools have previously demonstrated success in addressing the transonic interference effects within the wing-strut junction at high transonic Mach numbers typical of current single-aisle transport aircraft [21–23], this has not yet been shown to be possible for a cruise-slotted variant of the TTBW. However, this should not come as a surprise since the unique features of the cruise-slotted wing topology are positioned aft of the location where the strut intersects with the wing, which reduces its influence on the junction flow.

Figures 9c and 10c show the initial and optimized airfoils and pressure distributions. Following optimization, the steep pressure gradients on the initial wing upper surface of the TTBW-150 and TTBW-CS-150 designs have been smoothed to achieve gradual pressure recoveries, indicating that shock formation has been largely mitigated. For the optimized TTBW-CS-150, the pressure distributions indicate higher aft loading over the main element, with the high-speed slot flow from the wing lower surface appearing to help prevent boundary layer separation. The aft element is also highly loaded compared to a similar length of chord of the non-slotted wing. This leads to a more uniformly distributed chordwise loading with a fairly modest pressure recovery. However, the trade-off is that the swept wing now

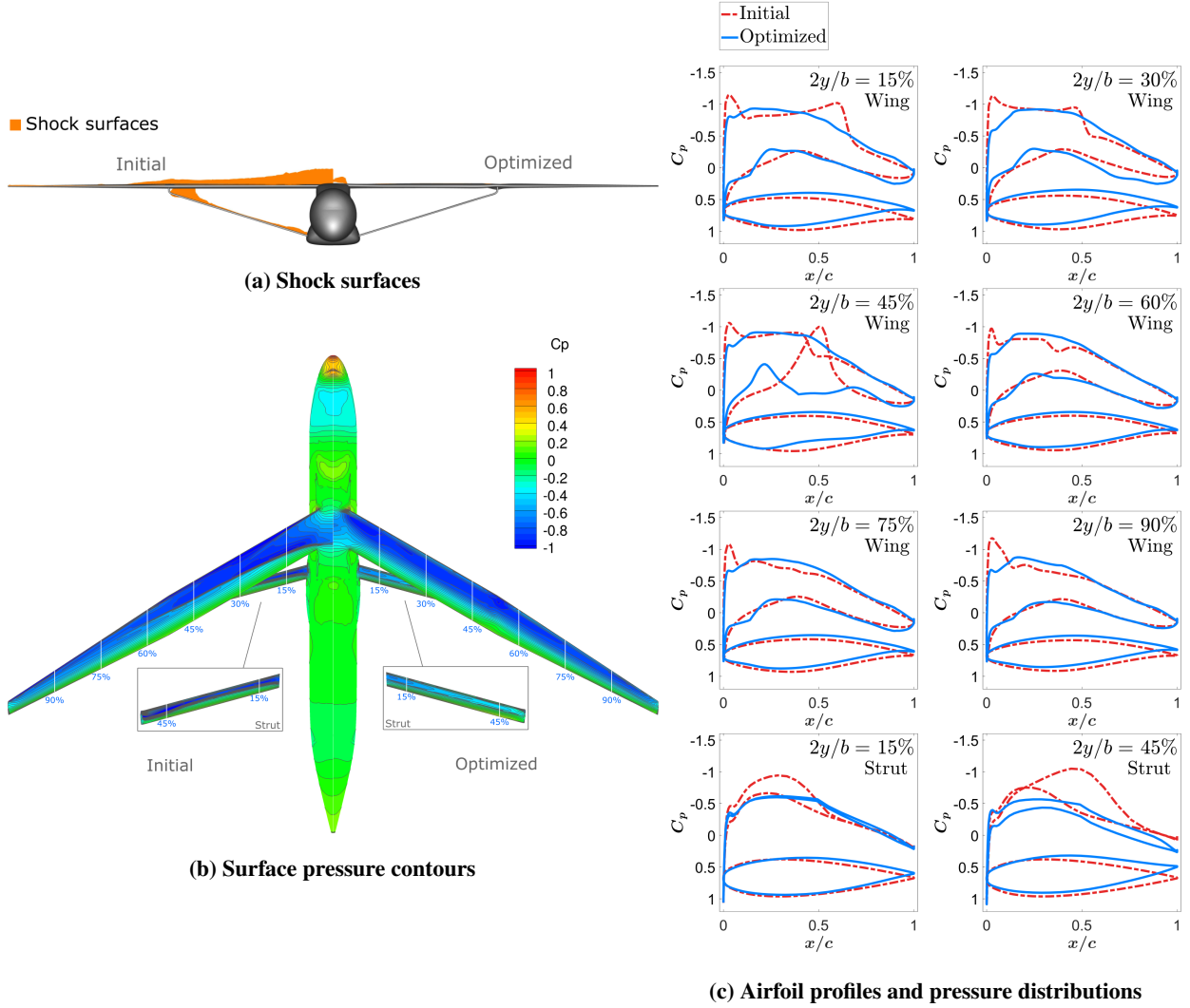


Fig. 9 TTBW-150: Initial and optimized design and flow features. Flow features are computed on the L0 grid level using Jetstream at $M = 0.800$ and $C_L = 0.560$.

produces more of a nose-down pitching moment, which results in trim drag penalties not accounted for in the present study.

Figures 9b and 10b show the initial and optimized surface pressure contours over the upper wing and strut surfaces. For the optimized TTBW-150, the pressure contours vary smoothly with well-aligned isobars. This is consistent with previous single-point optimization results [21, 23], which indicate good wave drag performance. On the other hand, although the surface pressure contours of the optimized TTBW-CS-150 approach a similar pattern over the main element, its contours are disrupted by non-uniform spanwise pressure distributions over the aft element. For example, the aft element experiences more load near the wing root, which tapers toward the intersection of the wing and strut. Nonetheless, it should be noted that such non-uniformities may be the result of a lack of geometric freedom available to the optimizer for more carefully tailoring the shape of the main and aft elements independently. Multipoint optimization could also aid in producing a design more similar to the optimized TTBW-150 when considering aerodynamic performance over a range of operating conditions.

With the optimization problems formulated as lift-constrained drag minimizations without constraints on pitching moment, the aerodynamic shape optimizations result in net spanwise lift distributions that are near elliptical. This is shown in Figures 11a and 11b for the TTBW-150 and TTBW-CS-150 configurations, respectively. For the optimized TTBW-150, the spanwise lift distribution over the wing features a local increase near the wing-strut junction, compensating for the

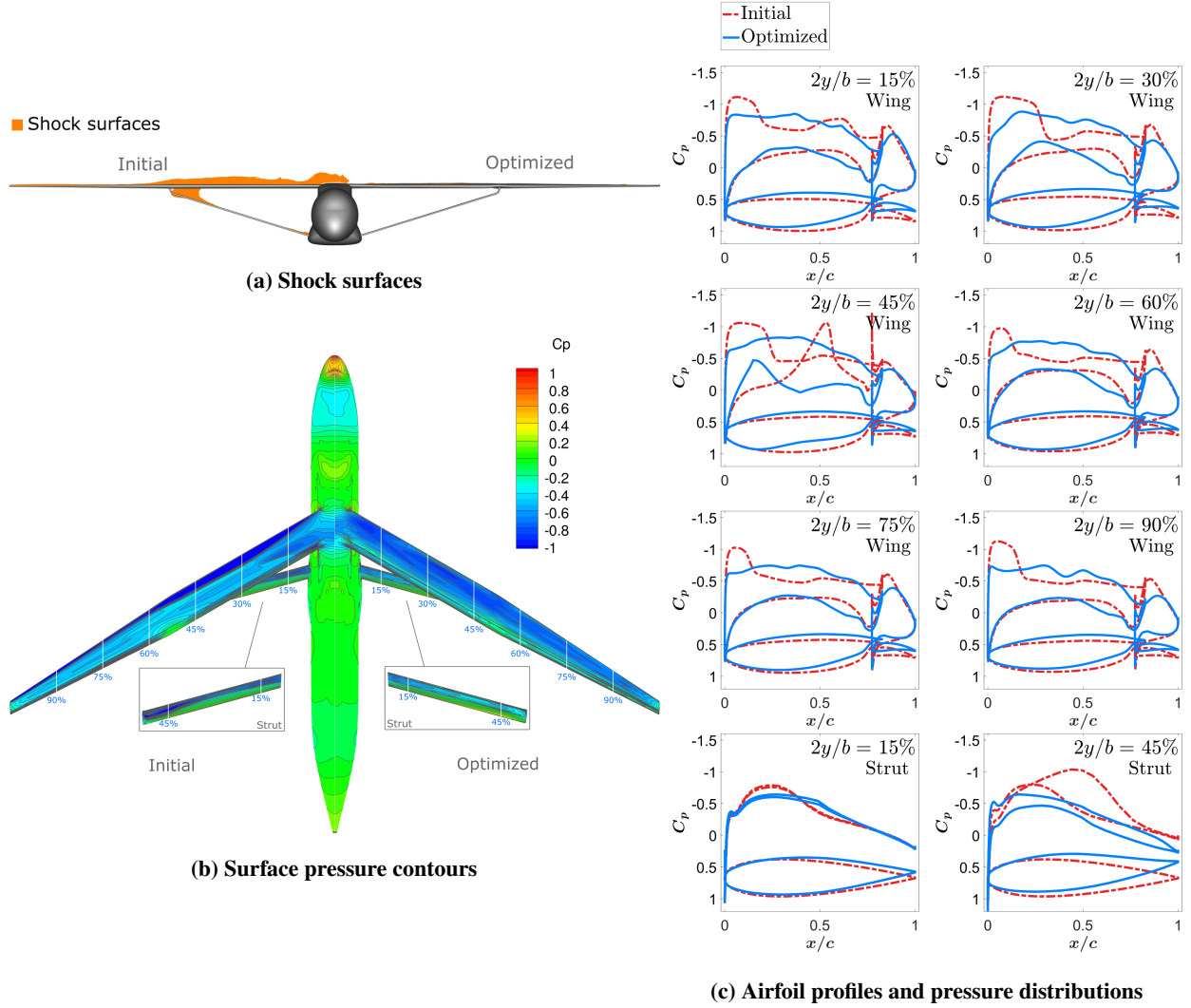


Fig. 10 TTBW-CS-150: Initial and optimized design and flow features. Flow features are computed on the L0 grid level using Jetstream at $M = 0.800$ and $C_L = 0.560$.

negative lift over the strut and achieving a relatively smooth elliptical distribution across the intersection. This negative strut lift was shown previously [20–23, 48] to be necessary for mitigating shock formation and, in some cases, boundary layer separation, which arises from the transonic channel effect. For the TTBW-CS-150 configuration, the optimizer is also capable of achieving a net spanwise lift distribution that is smooth and close to elliptical, despite the disruptions in the upper surface pressure contours observed in Figure 10c. The optimizer also introduces a similar positive and negative shift over the wing and strut, respectively, near the wing-strut junction. However, it is interesting that the lift compensation is carried only by the main element of the cruise-slotted wing, with the spanwise lift distribution over the aft element remaining smooth and relatively monotonic from root to tip.

Figures 12 and 13 show the initial and optimized wing and strut airfoils and pressure distributions near the wing-strut junction, providing a closer look at the local flow field. Note that sections A, B, C, and D correspond to 47%, 48%, 49%, and 50% semispan, respectively. Inner and outer wing-strut junction surface pressure contours are also included for reference. Here, it can be seen more clearly that, in the case of the initial geometries, the wing-strut junctions behave as transonic channels, accelerating the flow and causing a shock wave to develop. This comes in the form of sharp pressure drops on the lower wing surface of both aircraft configurations. More gradual pressure drops are also seen on the upper strut surfaces. By introducing an inset and bump on the lower wing surfaces, the optimizer is able to increase the pressure coefficient and mitigate this effect. This coincides with an outwards force distribution over the strut sections.

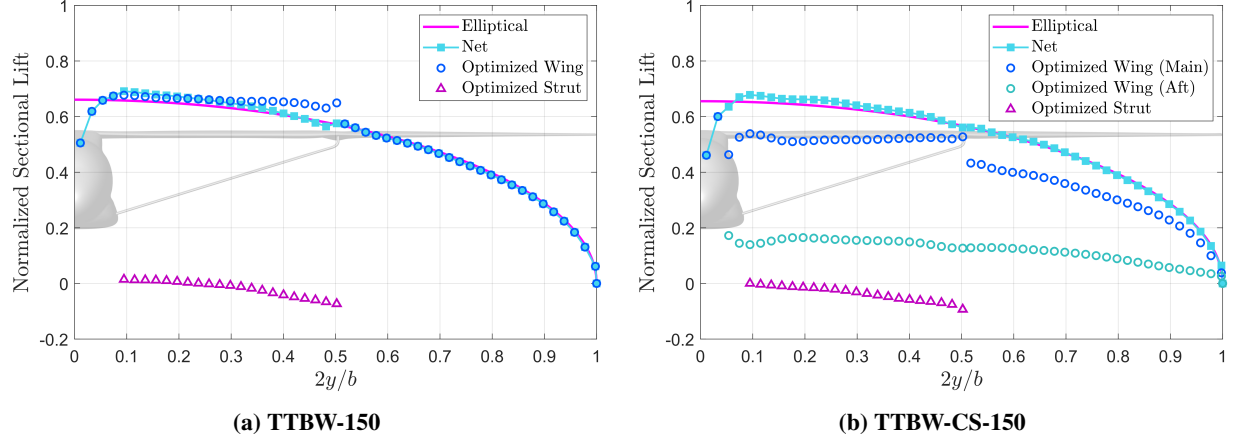


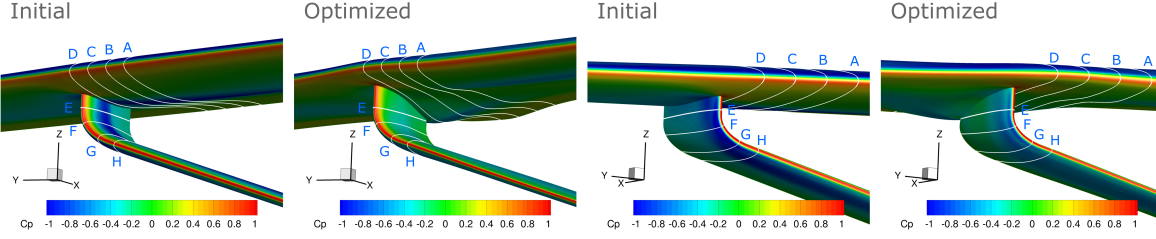
Fig. 11 Optimized spanwise lift distributions computed on the L0 grid level using Jetstream at $M = 0.800$ and $C_L = 0.560$.

Although these design features were also observed by Chau and Zingg [21–23], what is remarkable is that the optimizer opts to introduce a similar set of features for the cruise-slotted wing topology. Another important observation is that the optimizer does not appear to change the shape of the aft element much when reviewing Figures 10c and 13. However, this may be due to the lack of geometric freedom that comes as a consequence of designing the cruise-slotted wing as an integrated, single-element wing.

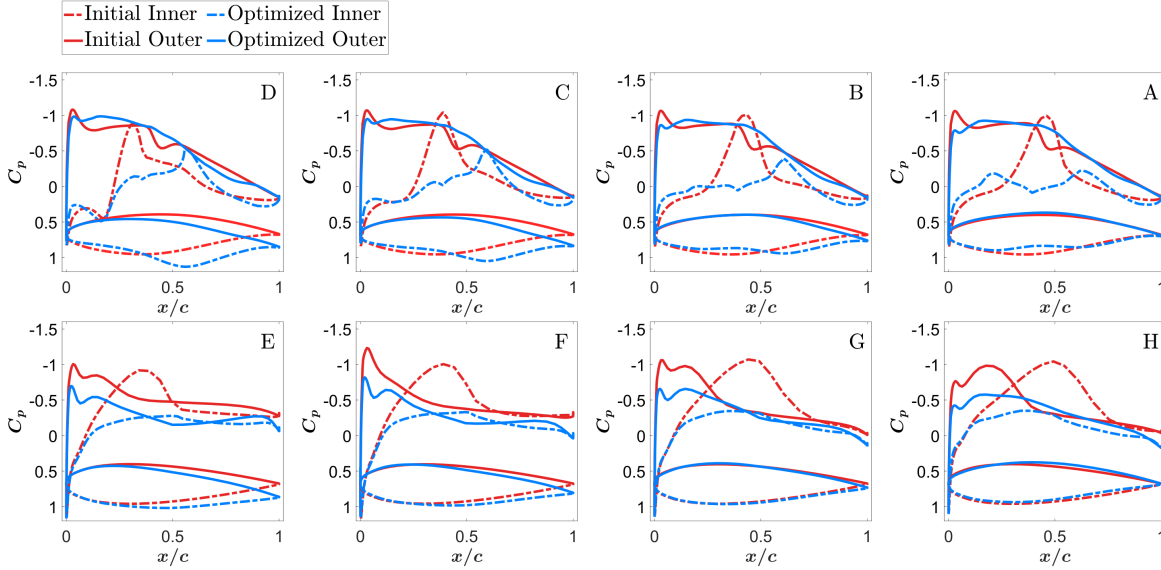
Table 6 presents the aerodynamic performance of the initial and optimized TTBW-150 and TTBW-CS-150 designs. Based on the results obtained from Jetstream on the optimization level (L0) grids, the optimized designs reduce drag by 17.5% and 19.3%, respectively, relative to the initial designs, while maintaining the design lift coefficient. Table 6 also includes estimates of the grid-converged aerodynamic functionals (L_∞) obtained through Richardson extrapolation. As described in Section II.B, post-optimization grid convergence studies are performed using the LAVA Curvilinear flow solver in order to reduce uncertainties from differences in grid resolution and topology between the computational grids of each aircraft configuration. These studies are shown in Figure 14, which illustrate monotonic convergence of the drag coefficient at constant lift for both configurations. Based on an assumed second-order rate of convergence, Richardson extrapolation indicates that the optimized TTBW-CS-150 experiences slightly more cruise drag than the optimized TTBW-150 at +3.2%, translating to a 2.7% deficit in lift-to-drag ratio at cruise. This is likely due to the increased wetted area of the multi-element wing, as well as the higher superelevations in and around the slot and aft element, which increases skin-friction drag.

Indeed, Hiller et al. [15] showed that the sectional skin-friction drag of a partial-span cruise-slotted wing is higher over the region of the slot than an equivalent conventional wing under the conditions of fully turbulent flow. Figure 15a shows a similar trend between the optimized TTBW-150 and TTBW-CS-150 designs, where the sectional skin-friction drag of the cruise-slotted wing is on average 18% greater than the non-slotted wing. For the cruise-slotted wing, the average sectional skin-friction drag of the main wing element alone is 91% that of the non-slotted wing, suggesting that the majority of the drag increase comes from increased skin-friction drag coefficients rather than increased wetted area. For reference, the average sectional skin-friction drag breakdown between the main and aft wing elements of the cruise-slotted wing is 77% and 23%, respectively, based on the results obtained on the optimization level grids. Figure 15b indicates that the optimized cruise-slotted wing also experiences similar sectional pressure drag compared to the non-slotted wing. This is consistent with the results of Hiller et al. [15], who found that the partial-span cruise-slotted wing had a similar sectional pressure drag distribution to that of the equivalently-designed conventional wing across the entire span in turbulent flow.

Figure 16 compares the skin-friction drag distributions at various spanwise stations of the optimized wings. For the slotted airfoils, the skin-friction drag coefficient increases toward the trailing edge of the main element and over the aft element due to the influence of the slot flow, leading to higher sectional skin-friction drag relative to the non-slotted airfoils. It is also interesting to note that just inboard of the wing-strut junction at 45% semispan, both the optimized TTBW-150 and TTBW-CS-150 wings experience an increase in the skin-friction drag coefficient upstream of where the shock waves initially form. This results from the optimizer’s solution to the transonic channel effect, which involves



(a) Surface pressure contours



(b) Airfoil profiles and pressure distributions

Fig. 12 TTBW-150: Initial and optimized surface pressure contours with inner (left) and outer (right) views of the strut, and (b) pressure distributions at different stations along the wing and strut. Results are computed on the L0 grid level using Jetstream at $M = 0.800$ and $C_L = 0.560$.

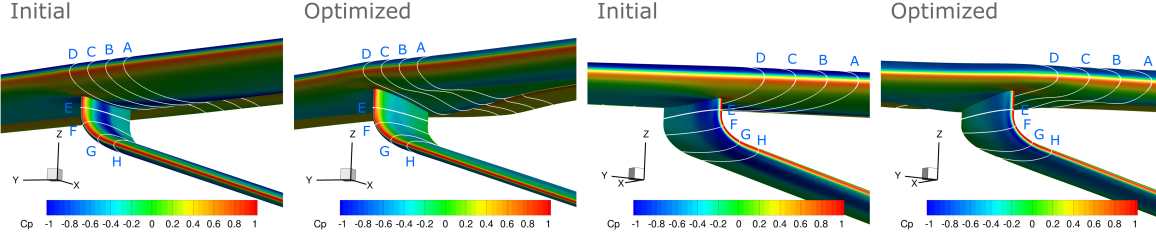
shifting the region of flow acceleration upstream to achieve an increase in local pressure.

Velocity magnitude contours are shown in Figure 17 at 15% semispan for both aircraft configurations. Here, it can be seen that the increased skin-friction drag of the aft element is due to accelerated flow on its suction side. These flow features are consistent with those at other spanwise stations across both wings.

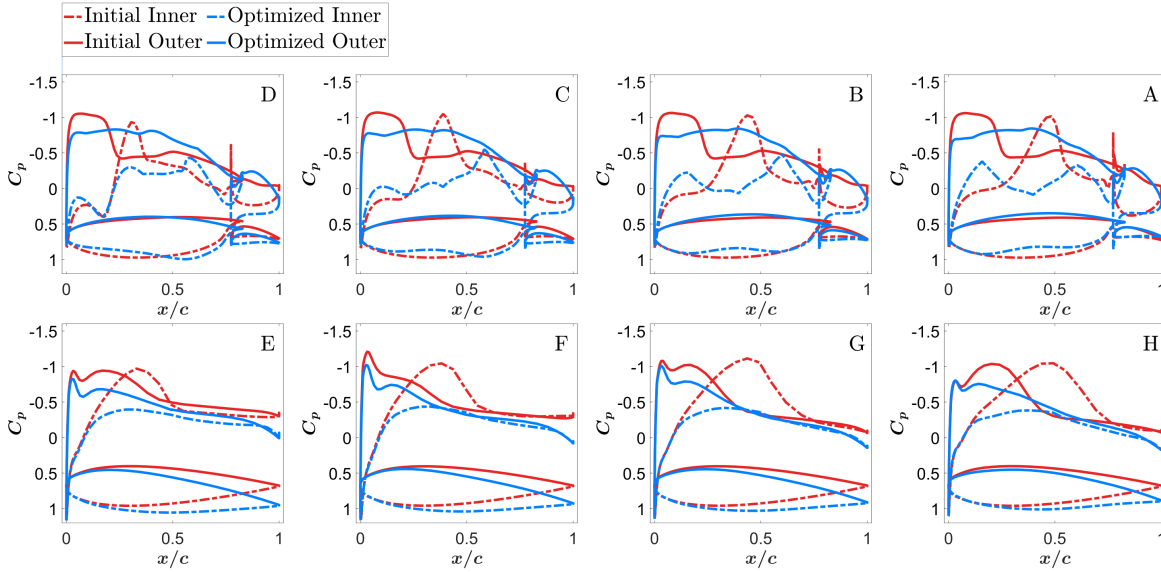
V. Mach Number Sensitivity Studies

As described in Section I, one of the main benefits of the cruise-slotted wing is its potential to achieve a similar maximum aerodynamic range efficiency, namely, $M(L/D)$ as that of a non-slotted wing, but at higher Mach numbers [13]. In principle, this would enable an improvement to airline productivity without compromising aircraft fuel efficiency. In this section, Mach number sensitivity studies are performed to investigate this hypothesis for the cruise-slotted variant of the TTBW. Specifically, the optimized TTBW-150 and TTBW-CS-150 designs presented in Section IV.D are analyzed over a range of Mach numbers, from Mach 0.740 to 0.830, trimmed with respect to angle of attack to maintain the design lift coefficient, and compared with one another.

Results indicate that the cruise-slotted variant of the TTBW experiences a more gradual drag rise than the non-slotted TTBW, but the maximum $M(L/D)$ remains lower for the TTBW-CS-150 configuration due to the drag penalties described in Section IV.D. Because the single-point optimizations at Mach 0.800 led to the elimination of most, if not all, of the wave drag encountered by the initial TTBW-150 and TTBW-CS-150 designs, it was posited that the benefit of the cruise-slotted wing's increased airfoil technology factor could not manifest as an aerodynamic trade advantage over



(a) Surface pressure contours



(b) Airfoil profiles and pressure distributions

Fig. 13 TTBW-CS-150: Initial and optimized surface pressure contours with inner (a, left) and outer (a, right) views of the strut, and (b) pressure distributions at different stations along the wing and strut. Results are computed on the L0 grid level using Jetstream at $M = 0.800$ and $C_L = 0.560$.

the non-slotted wing. This is especially the case at the design point, as discussed in Section IV.D, where the increased skin-friction drag experienced by the optimized TTBW-CS-150 led to higher overall drag compared to the optimized TTBW-150 since both configurations experienced similar pressure drag and minimal wave drag. In practice, transonic wing designs typically maintain some wave drag as a component of the aerodynamic trades, whether for reasons of aerodynamic efficiency, performance robustness, or airline productivity. This is supported in part by investigations involving multipoint optimization, where weak to moderate shocks often remain on the upper surfaces of optimized airfoils and wings. See for example, Nemec et al. [49], Kenway and Martins [50], and Chau and Zingg [22, 23].

This motivates the need for multipoint optimizations of the TTBW-150 and TTBW-CS-150 configurations. However, to reduce computational cost, the present study instead repeats the single-point optimizations but at higher design Mach numbers. Specifically, design Mach numbers of 0.815 and 0.830 are considered for the additional designs under the assumption that the optimizer will make compromises in the form of wave drag when asked to push the envelope of the aerodynamic designs. These additional design optimizations consider the same problem formulations as those presented in Section IV.C and are converged to similar optimization tolerances. All optimized designs are also based on the same aircraft concept described in Section III.

Figure 18 shows the initial and optimized shock surfaces for all six of the optimized designs, while optimized pressure distributions are included in Figure 19. From Figure 18, it can be seen that as the initial designs are operated at successively higher Mach numbers, the shock waves grow in strength as expected. However, what is surprising is that the optimizer is capable of nearly completely mitigating shock formation across all of the wing and strut designs, even

Table 6 Aerodynamic performance of the initial and optimized designs computed on the optimization level grids (L0) using Jetstream. Estimates of the grid-converged aerodynamic functionals (L_∞) for the optimized designs are also included based on LAVA Curvilinear flow solutions.

Parameter	Initial (L0)	Optimized (L0)	Δ (L0)	Optimized (L_∞)
TTBW-150				
Angle of attack, deg	1.78	2.00	— —	— —
Lift coefficient	0.560	0.560	— —	0.560
Drag coefficient	0.0285	0.0235	-17.5%	0.0216
Lift-to-drag ratio	19.6	23.8	+21.4%	25.9
TTBW-CS-150				
Angle of attack, deg	1.21	2.00	— —	— —
Lift coefficient	0.560	0.560	— —	0.560
Drag coefficient	0.0311	0.0251	-19.3%	0.0223
Lift-to-drag ratio	18.0	22.3	+23.9%	25.2

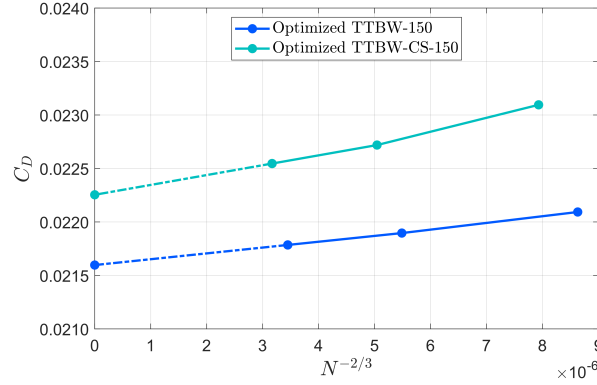


Fig. 14 Grid-convergence studies performed using the LAVA Curvilinear flow solver at $M = 0.800$ and $C_L = 0.560$. Richardson extrapolation is performed assuming second-order convergence.

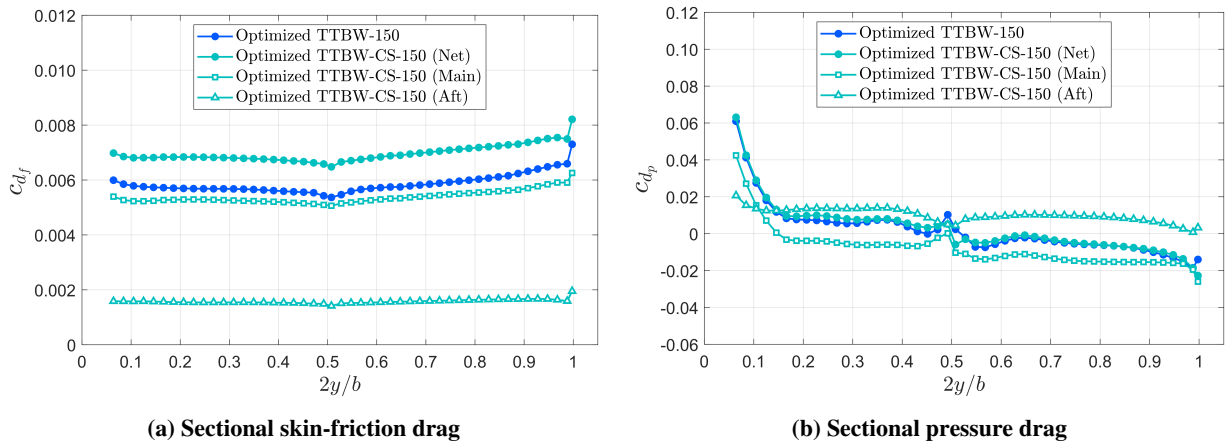


Fig. 15 Optimized sectional wing skin-friction and pressure drag coefficients computed on the L0 grid level using Jetstream at $M = 0.800$ and $C_L = 0.560$.

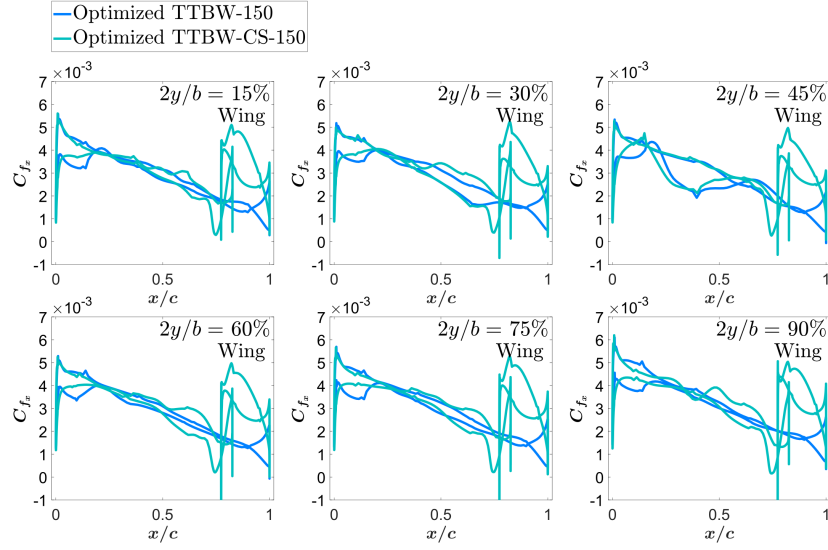


Fig. 16 Skin-friction drag distributions over the wings of the optimized TTBW-150 and TTBW-CS-150 designs, computed on the L0 grid level using Jetstream at $M = 0.800$ and $C_L = 0.560$.

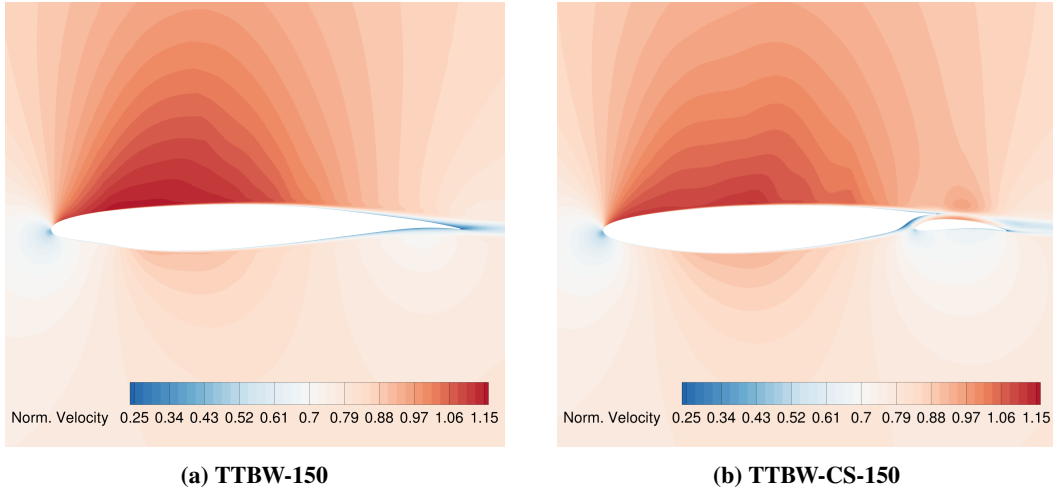


Fig. 17 Velocity magnitude contours at 15% semispan, normalized by freestream conditions, for the optimized TTBW-150 and TTBW-CS-150 designs. Solutions are computed on the L0 grid level using Jetstream at $M = 0.800$ and $C_L = 0.560$.

when the design Mach number is increased to 0.830. The wing-strut junctions also remain shock-free for all optimized designs. This is consistent with the pressure distributions shown in Figure 19, which remain relatively smooth across all design Mach numbers.

Although the unexpected success of the single-point optimizations reinforce the need for investigations involving multipoint optimization, the Mach number sensitivity studies are nonetheless performed for all six configurations. In order to estimate the grid-converged aerodynamic functionals at each operating point, as done previously in Section IV.D, grid-convergence studies are first performed. These are performed on the grid families presented in Section IV.B for the Mach 0.800 designs, as well as grid families generated for the TTBW-150 and TTBW-CS-150 designs optimized at Mach 0.815 and 0.830, which are developed with similar grid properties. From Figure 20, it can be seen that monotonic convergence of the drag coefficient is obtained over each grid level, improving the credibility of the Richardson extrapolations.

Figure 21 presents the drag rise and aerodynamic range efficiency curves for the Mach 0.815 and 0.830 TTBW-150

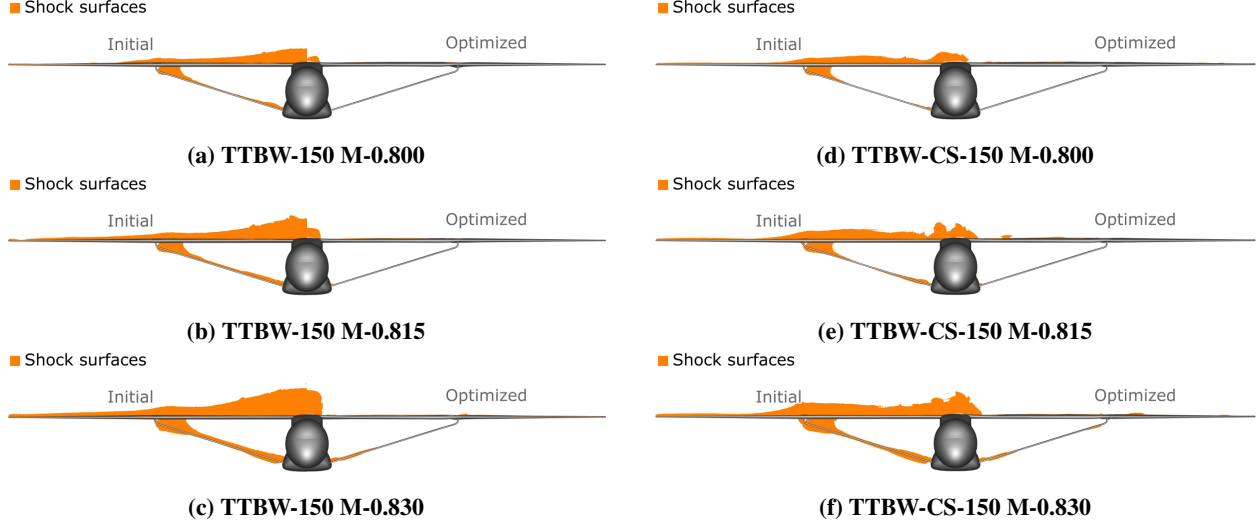


Fig. 18 Initial and optimized design-point shock surfaces computed on the L0 grid level using Jetstream at $C_L = 0.560$.

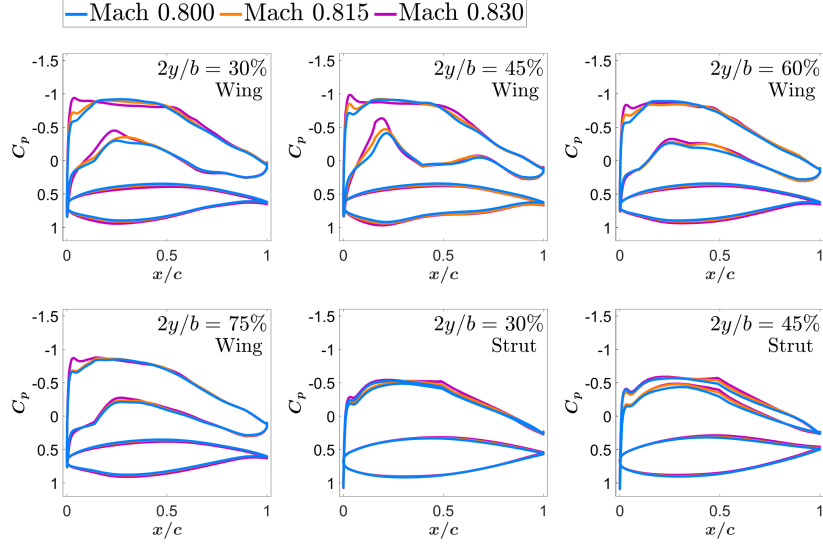
and TTBW-CS-150 designs, as well as those of the Mach 0.800 designs previously discussed in this section. From Figure 21a, it can be seen that for each configuration, as the design Mach number is increased, the drag rise becomes more gradual within the Mach 0.800 to 0.830 range. This comes at the cost of increased drag at Mach numbers below 0.800. However, when comparing the optimized TTBW-150 and TTBW-CS-150 configurations developed for a given design Mach number, it can be seen that the cruise-slotted wing topology results in a more gradual drag rise than the non-slotted variant as the operating Mach number is increased. This trend comes with diminishing returns, with the advantage reducing most significantly when the design Mach number is increased to 0.830.

Figure 21b shows that for a given configuration, as the design Mach number is increased, the location of maximum $M(L/D)$ shifts to higher Mach numbers. The maximum $M(L/D)$ also increases with the design Mach number for the optimized TTBW-CS-150 but not for the optimized TTBW-150. However, the expected cross-over in the $M(L/D)$ curves as the design Mach number is increased does not occur, leaving the optimized TTBW-CS-150 at a performance deficit in terms of maximum $M(L/D)$ relative to the optimized TTBW-150 for all design Mach numbers. Although consistent with Figure 2, this penalty appears larger than what is proposed by Vassberg et al. [13]. It is also important to note that Figure 21b presents $M(L/D)$ across a range of Mach numbers at constant lift coefficient and Reynolds number, while Figure 2 shows the maximum $M(L/D)$ as a function of Mach number.

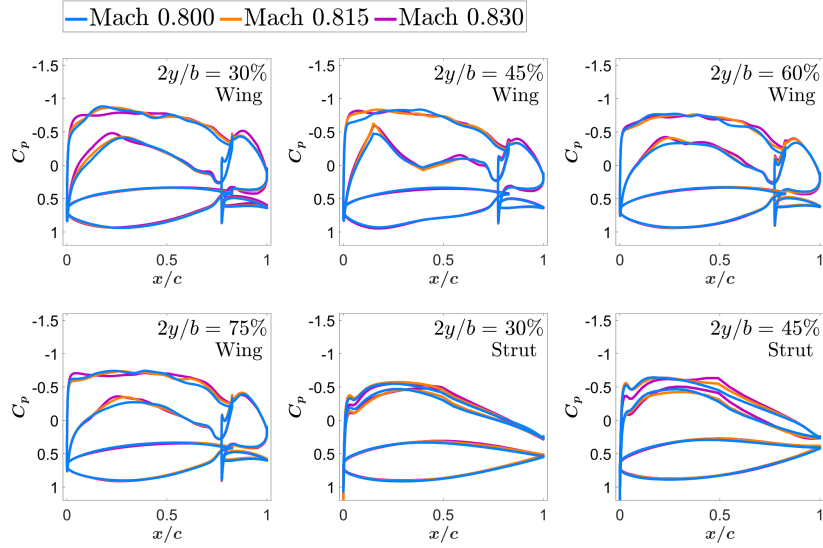
VI. Conclusions

This paper investigates the aerodynamic design and performance of a Mach 0.800, single-aisle, cruise-slotted TTBW configuration developed for turbulent flow through the application of aerodynamic shape optimization based on the RANS equations. Gradient-based optimization is used to minimize vehicle drag at cruise with respect to wing and strut twist and section shape design variables, while subject to constant lift and minimum wing and strut volume constraints, and several other geometric constraints introduced to maintain concept feasibility. Optimization is performed on geometric models consisting of a wing, strut, and fuselage, and include the cruise-slotted TTBW or TTBW-CS-150 configuration, as well as a non-slotted TTBW or TTBW-150 configuration, the latter serving as a reference aircraft.

Results indicate that at the design point, the optimizer is capable of achieving aerodynamically efficient designs for both the TTBW-150 and TTBW-CS-150 configurations. This includes smooth wing and strut pressure distributions, near elliptical spanwise lift distributions, and minimal wave drag. With regard to wave drag, the optimizer was also found to be successful in mitigating the transonic channel effect unique to truss-braced wings operating at high transonic Mach numbers typical of single-aisle aircraft. Moreover, mitigation of shock formation in and around the wing-strut junction of the TTBW-CS-150 configuration involved remarkably similar design features to those of the optimized TTBW-150, including an outwards force distribution, and novel bumps and insets to control local pressure drops due to sudden accelerations of the flow. However, comparisons of on-design aerodynamic performance between the two configurations



(a) TTBW-150



(b) TTBW-CS-150

Fig. 19 Optimized pressure distributions for the Mach 0.800, 0.815, and 0.830 designs of the TTBW-150 and TTBW-CS-150 configurations operating at the design Mach numbers and $C_L = 0.560$. Solutions are computed on the L0 grid level using Jetstream

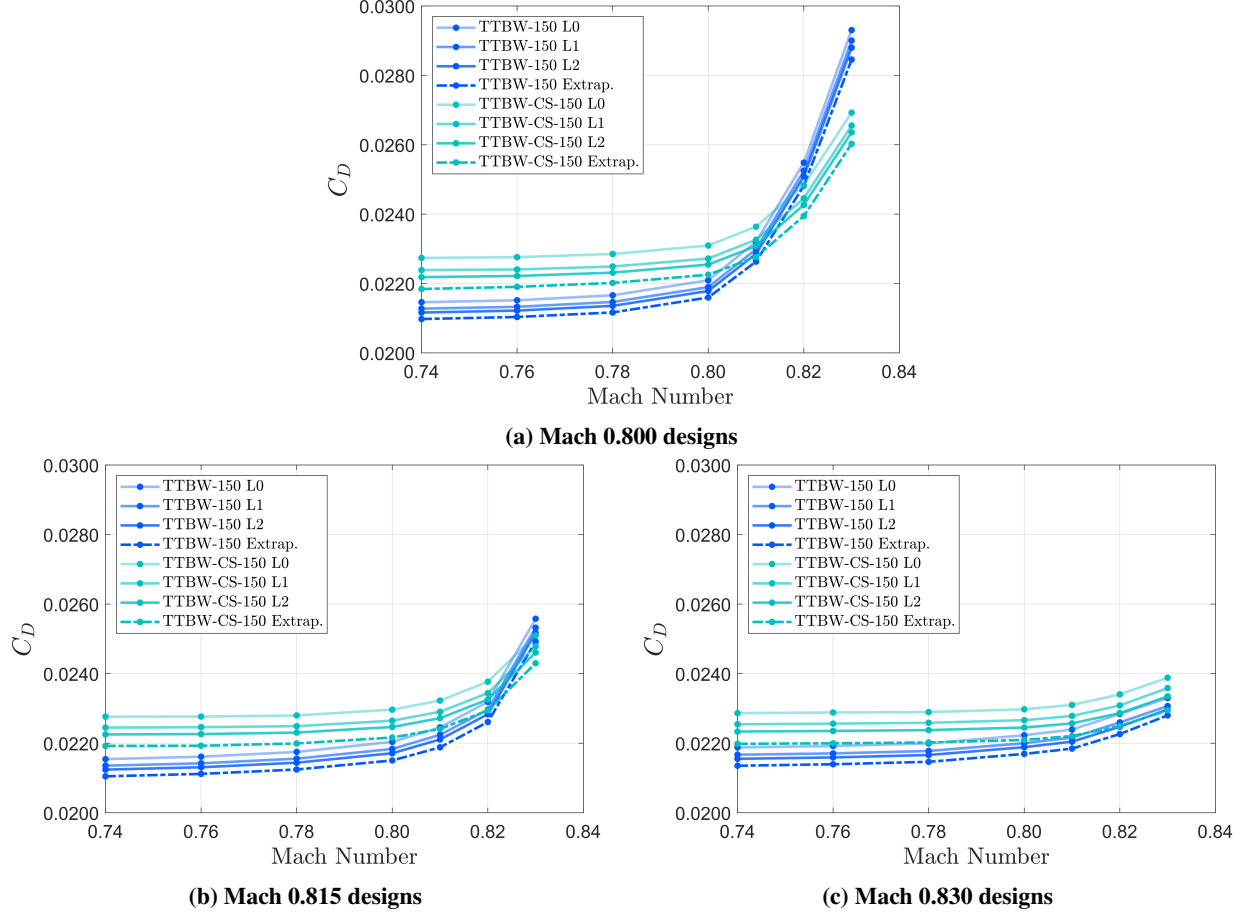


Fig. 20 Grid-convergence studies performed using the LAVA Curvilinear flow solver to estimate grid-convergence aerodynamic functionals at each operating condition.

indicate that the optimized TTBW-CS-150 experiences 3.2% more drag than the optimized TTBW-150, which translates to a lift-to-drag ratio deficit of approximately 2.7%. This was found to be due to both higher skin-friction and pressure drag across the wing span, likely arising from the slotted region.

Mach number sensitivity studies are also performed for both the TTBW-150 and TTBW-CS-150 configurations. Results show that the TTBW-CS-150 configuration does not provide a maximum $M(L/D)$ benefit over the TTBW-150, even at higher operating Mach numbers. This remains to be the case when comparing configurations optimized for higher design Mach numbers. However, this may be due to the unexpected success of the single-point optimizations in eliminating nearly all sources of wave drag over the wing and struts, leaving the airfoil technology factor advantage of the cruise-slotted wing with minimal impact. Nonetheless, for all optimized TTBW-CS-150 designs, the cruise-slotted wing topology was found to lead to more gradual rises in drag as Mach number is increased compared to the optimized TTBW-150 configurations. This suggests that the potential advantage of the cruise-slotted wing can manifest itself if the wing system is designed under more practical considerations, such as performance robustness via multipoint optimization. This would likely lead to the return of wave drag trades, in which the cruise-slotted wing is well-positioned.

Overall, aerodynamic shape optimization based on the RANS equations is successful in demonstrating that an efficient and viable cruise-slotted TTBW configuration can be developed for the single-aisle class, with optimal design features very much similar to an equivalent non-slotted TTBW configuration. However, more work is required to minimize the impact of operating at higher cruise Mach numbers on maximum aerodynamic range efficiency when considering fully turbulent flow conditions. One can also consider the introduction of natural laminar flow, as demonstrated by Hiller et al. [14, 15]. This is reserved for future work.

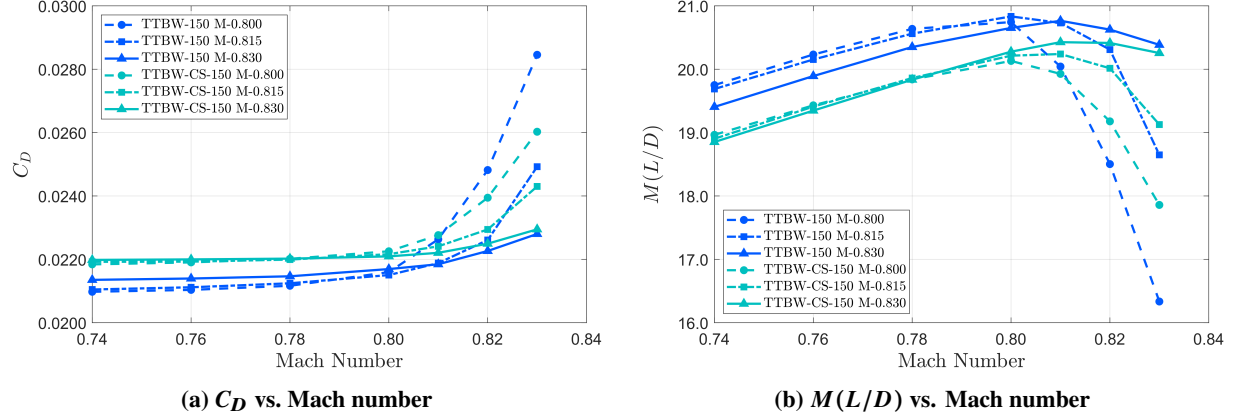


Fig. 21 Drag rise and aerodynamic range efficiency curves for TTBW-150 and TTBW-CS-150 configurations optimized for Mach 0.800, 0.815, and 0.830. These solutions are computed using the LAVA Curvilinear flow solver at $C_L = 0.560$ and $Re = 12.12 \times 10^6$.

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