

Propulsion-Airframe Integration for Conceptual Redesign of a Low-Boom Supersonic Transport

Wu Li* and Karl Geiselhart†

NASA Langley Research Center, Hampton, Virginia 23681, USA

A low-boom supersonic transport was generated in a previous low-boom multidisciplinary optimization (MDO) study that used computational fluid dynamics (CFD) off-body pressure to compute the undertrack sonic boom ground signature and calibrated low-fidelity aerodynamic analyses to compute the mission performance metrics. This low-boom aircraft, referred to as the Mach 1.7 40-PAX concept, can carry 40 passengers for a low-boom overland mission with cruise Mach 1.7 for the airport pairs over the continental US and has the potential to achieve an undertrack sonic boom ground noise level below 70 perceived level of decibels at the start of overland cruise (SOC). The engine for the Mach 1.7 40-PAX concept was designed using the Numerical Propulsion System Simulation (NPSS) for the mission analysis and modeled as a flow-through nacelle for CFD-based sonic boom analysis. To understand how the engine plume affects the undertrack ground signature, the Mach 1.7 40-PAX concept is redesigned in this paper after replacing the flow-through nacelles with CFD engines for sonic boom analysis using aeropropulsive CFD simulation. A process is developed for approximation of the NPSS engine at SOC by a CFD engine for aeropropulsive CFD simulation. The generated CFD engine has the identical nozzle boundary conditions and approximately the same mass flow and thrust as those of the NPSS engine at SOC. Then, the outer mold line of the configuration with the CFD engines is redesigned to approximately restore the low-boom characteristics of the Mach 1.7 40-PAX concept at SOC. Finally, the CFD simulation data for the redesigned concept with the CFD engines is used to calibrate the low-fidelity aerodynamic analyses for mission analysis of this concept. The cyclic dependency of the involved disciplinary analyses is resolved using an iteration method for a consistent coupling of the mission analysis, NPSS engine analysis, and low-boom redesign using the aeropropulsive CFD simulation. This low-boom redesign study is used as an example to demonstrate how the propulsion-airframe integration could be implemented for conceptual design of supersonic transports that satisfy both the low-boom and mission performance requirements.

Nomenclature

$\ \cdot\ $	= 2-norm of a function f on interval $[0, l_e]$ defined by $\ f\ $, which equals $\left(\int_0^{l_e} f(t) ^2 dt / l_e\right)^{\frac{1}{2}}$
A_e	= any equivalent area, including $A_{e,r}$ and $A_{e,CFD}$, ft^2
$A_{e,CFD}$	= equivalent area defined using Mach angle cut method and computational fluid dynamics, ft^2
$A_{e,r}$	= reversed equivalent area defined by using reverse propagation of off-body pressure, ft^2
$A_{e,r}(\mathbf{D})$	= $A_{e,r}$ for $\mathbf{D}$, ft^2
$A_{e,r}^{\text{target}}(\mathbf{D})$	= $A_{e,r}$ target for $\mathbf{D}$, ft^2
$CG_{x,\text{aft}}$	= most aft longitudinal center of gravity at SOC using fuel redistribution for $\mathbf{D}$, ft
$CP_{x,CFD}$	= longitudinal center of pressure at SOC for $\mathbf{D}$ from computational fluid dynamics analysis, ft
C_L	= lift coefficient
d	= diameter of cross section of axisymmetric engine, used with different subscripts, ft
$\mathbf{D}$	= vector of aircraft geometry parameters, shape parameters for $A_{e,r}^{\text{target}}$, H_{OL} , R_{OL} , θ_{tail} , and sea-level static thrust for engine
dp/p	= nondimensional overpressure $(p-p_\infty)/p_\infty$
g_i	= constraint function for mission constraint computed using the calibrated lift method
H_{OL}	= cruise altitude for overland mission or for computational fluid dynamics analysis, ft

* Senior Research Engineer, Aeronautics Systems Analysis Branch

† Aerospace Engineer, Aeronautics Systems Analysis Branch

$\mathbf{l}$	= lower-bound vector for $\mathbf{D}$
l_e	= effective length of a configuration, which is the largest effective distance where Mach angle cut plane intersects the configuration, ft
l_{th}	= distance from inlet throat to fan face, ft
l_{spike}	= distance from spike tip to fan face, ft
M	= cruise Mach for overland flight
MTOGW	= maximum takeoff gross weight of aircraft, lb
p	= longitudinal pressure distribution at undertrack location below aircraft, lb/ft ²
p_∞	= ambient pressure, lb/ft ²
PLdB($A_{e,r}$)	= perceived level in decibels of sonic boom ground signature for $A_{e,r}$
R_{OL}	= range for overland mission of $\mathbf{D}$, nm
r_{sp}	= static pressure ratio at fan face of engine
SOC	= start of overland cruise
TOGW _{OL}	= takeoff gross weight for overland mission of $\mathbf{D}$, lb
$\mathbf{u}$	= upper-bound vector for $\mathbf{D}$
U_∞	= freestream velocity at SOC, ft/s
x, y, z	= coordinates of point in space, ft
x_e	= effective distance for A_e , ft
$x_{e,tte}$	= x_e location corresponding to trailing edge of wing tip airfoil, ft
y_{it}	= calibration parameter for span location to truncate wing for low-fidelity aerodynamic analysis, ft
W_{crs}	= weight at SOC, lb
3BL	= three body lengths
α	= angle of attack at SOC, deg
β	= Prandtl-Glauert factor $\sqrt{M^2 - 1}$
ε	= tolerance for acceptable low-boom inverse design objective value
φ	= angle as shape parameter for axisymmetric engine, used with different subscripts, deg
θ_{htail}	= deflection angle of an all-moving horizontal tail at SOC, deg
θ_Δ	= calibration parameter for θ_{htail} , deg
ρ_∞	= ambient density at SOC, lb/ft ³

I. Introduction

THE ban on commercial supersonic flights overland is a key barrier for development of commercial supersonic aircraft. To lift the ban on supersonic flights overland, NASA has been developing low-boom technologies that could enable a commercially successful supersonic transport to fly overland with a quiet sonic thump, rather than a loud sonic boom, on the ground. The NASA N+3 low-boom goal [1] is that a commercial supersonic transport will only create sonic boom ground signatures with perceived levels of decibels (PLdB) [2] below 70, which is significantly lower than the sonic boom loudness exceeding 100 PLdB for Concorde {see page 6 of Ref. [1]}. The X-59 QueSST [3] {see Ref. [4] for a preliminary geometry model of the X-59 QueSST}, NASA's quiet supersonic experimental aircraft, was designed by Lockheed Martin using computational fluid dynamics (CFD) based low-boom shaping technologies to demonstrate a sonic thump of about 75 PLdB on the ground. While low-boom shaping technologies have been reasonably matured, the strongly coupled conflict between an aerodynamically efficient shape and a low-boom shape for the outer mold line (OML) of a commercial supersonic transport was only recently resolved, at a conceptual level, by a multi-objective multidisciplinary optimization (MDO) method called the block coordinate optimization (BCO) method. The BCO method dissects a multi-objective low-boom MDO problem into six weakly coupled optimization subproblems and solves the optimization subproblems successively and repeatedly to find a low-boom supersonic transport that also satisfies the specified mission performance requirements [5]. The "low-boom" qualifier means the potential to achieve an undertrack sonic boom ground noise level below 70 PLdB at the start of overland cruise (SOC). The specified mission performance requirements include a low-boom overland mission for airport pairs over the continental US and an unrestricted overwater mission for transatlantic commercial flights. The low-boom supersonic transport in Ref. [5] with a more detailed cabin layout will be referred to as the Mach 1.7 40-PAX concept because it has a low-boom cruise Mach of 1.7 and carries 40 passengers.

The engine on the Mach 1.7 40-PAX concept is a variable cycle engine (VCE) with an acoustic shield to mitigate jet noise on takeoff. It was developed by NASA's Glenn Research Center {see Ref. [6]} using the Numerical Propulsion System Simulation (NPSS) [7]. NPSS is used to generate the engine weight and performance data for mission analysis of the Mach 1.7 40-PAX concept. For full-vehicle CFD analyses, the VCE was modeled as a flow-

through nacelle to generate CFD off-body pressure for sonic boom analysis. To understand what it takes to restore the low-boom characteristics after replacing a flow-through nacelle with a powered engine, the Mach 1.7 40-PAX concept is redesigned in this paper using an aeropropulsive CFD simulation for sonic boom analysis.

A powered engine for aeropropulsive CFD simulation is usually modeled by a CFD engine with inflow and outflow boundary conditions (BCs). The published studies of supersonic aircraft with CFD engines cover off-body pressure and ground signature calculations for two low-boom demonstrators with a single engine {see the summary results and relevant references in Refs. [4,8]}, optimization of inlet and nozzle shapes of an engine on a supersonic business jet [9], plume shapes for various nozzles of an engine on a low-boom concept [10], evaluations of aerodynamic drag and intake performance of a supersonic business jet using different engines [11], adjoint-based low-boom shaping of a supersonic demonstrator with a single engine [12,13], effects of different engines on ground signatures of two low-boom configurations with and without nozzle shock shielding [14], static aeroelastic analysis of a supersonic configuration with engines [15], and impacts of different engines on ground signatures of a low-boom configuration [16,17].

While most propulsion-airframe integration studies are focused on the aerodynamic influences of engines on the airframe using a CFD simulation or vice versa, some studies also explore the coupling interactions between the propulsion system and airframe. In Refs. [14,16], the effects of an installed engine on off-body pressures and ground signatures of a low-boom supersonic configuration were studied, while the required thrust for the low-boom configuration at the specified cruise condition was matched by the installed engine. The primary focus of Ref. [15] was to provide a means to include relevant dynamics of a turbomachinery propulsion system into the aeroelastic study. In this study, a variable cycle turbofan engine was coupled with a CFD engine for the proposed integration method. The CFD mass flows at the boundary faces were used by the turbofan engine analysis. For a consistent coupling, the turbofan engine analysis was planned to provide the updated BCs for the aeropropulsive CFD simulation; but fixed engine BCs were used in CFD analysis to allow for a partial inclusion of the propulsion system impacts while maintaining a stable solution. Coupling between an NPSS engine and a CFD engine was also attempted in Ref. [13] for design of a low-boom supersonic demonstrator. In Ref. [13], the inlet performance map from the aeropropulsive CFD simulation was used by the NPSS engine to determine the inlet total pressure recoveries, mass flows, and distortion limits for the CFD engine. Moreover, the initial CFD engine for the supersonic demonstrator used the NPSS nozzle BCs, achieved the mass flow balance, and matched the required engine thrust at the low-boom cruise condition. Note that the thrust term used in this paper refers to the net thrust per engine. This initial engine along with the aft shape of the aircraft was reshaped using an adjoint-based inverse design optimization method to obtain a low-boom configuration with a CFD engine that had an undertrack ground noise level of 75.0 PLdB. The resulting low-boom configuration with a CFD engine had slightly worse drag and lift-to-drag ratio than the baseline with a flow-through nacelle. A fully coupled integration of the propulsion system and airframe was only achieved in a study of the potential benefits of boundary layer ingestion for subsonic aircraft [18]. An MDO iteration method was used to achieve the coupling consistency between a one-dimensional thermodynamic cycle analysis and a CFD simulation of an aft-fuselage engine on a subsonic fuselage-wing-tail configuration. The CFD simulation of the engine was implemented using an actuator zone instead of BCs. The coupling variables for the two different engine analyses included the static pressure, flow velocity, and area for the fan face, as well as the mass flow.

For coupling of low-boom shaping and aeropropulsive CFD simulation, the existing studies were not able to obtain a low-boom configuration with the required cruise lift [12,13]. This lift inconsistency issue was only explicitly discussed in Ref. [12]. The low-boom shaping [12] was performed for a low-boom flight demonstrator of one seat, one engine, a body length of 108 ft, a wingspan of 30 ft, a cruise Mach of 1.6, a cruise altitude of 51,700 ft, and a cruise weight of 21,000 lb. The predicted undertrack ground noise level for the optimal design with a flow-through nacelle was 74.2 PLdB at the specified cruise Mach and altitude. After replacing the flow-through nacelle with a CFD engine, the aft ground signature shape changed significantly, and the undertrack ground noise level increased from 74.2 to 80.7 PLdB. The reshaping of the configuration with the CFD engine led to the final low-boom design with an undertrack ground noise level of 76.4 PLdB, but the lift coefficient of 0.059 for the final low-boom design was significantly lower than the required 0.065 for the cruise weight of 21,000 lb.

The propulsion-airframe integration in this paper is for conceptual design of supersonic transports that satisfy both the low-boom and mission performance requirements. The aeropropulsive CFD simulation uses Cart3D [19], a solver for the Euler equations. The coupling scope includes the mission analysis, NPSS engine analysis, and low-boom shaping of an aircraft concept with CFD engines. It starts with extracting the required engine thrust at SOC from the mission analysis data of the Mach 1.7 40-PAX concept. Then, the relevant dimension and performance parameters of the VCE for the required engine thrust at SOC are extracted from the NPSS engine analysis data. A CFD engine is constructed with approximations of the relevant NPSS engine parameters, while the CFD engine thrust matches the VCE thrust at SOC. Next, the flow-through nacelles of the Mach 1.7 40-PAX concept are replaced with the CFD

engines for sonic boom analysis using the aeropropulsive Cart3D simulation. The pylon twist angle and tail deflection angle of the configuration with the CFD engines are redesigned to approximately restore the low-boom characteristics of the Mach 1.7 40-PAX concept. Finally, the mission analysis is repeated for the low-boom concept with the CFD engines using the calibrated low-fidelity aerodynamic analyses based on the aeropropulsive Cart3D simulation data for the same concept. An iterative method is used to achieve the coupling consistency for all the disciplinary analyses.

This low-boom redesign study illustrates how the propulsion-airframe integration could be consistently implemented for conceptual design of low-boom supersonic transports. This paper also advances the state of the art of low-boom optimization using aeropropulsive CFD simulation for conceptual design of supersonic transports. It demonstrates that an acceptable low-boom concept can be generated while satisfying the cruise lift constraint and achieving the coupling consistency between the NPSS engine analysis and the aeropropulsive Cart3D simulation using the nozzle BCs, mass flow, and engine thrust as the coupling variables. Here an acceptable low-boom concept means that its reversed equivalent area ($A_{e,r}$) [20] closely matches an $A_{e,r}$ target with an undertrack sonic boom ground noise level below 70 PLdB [see Eq. (1) for the mathematical definition].

The paper is organized as follows. The CFD analysis method is described in Sec. II. Details of the Mach 1.7 40-PAX concept are provided in Sec. III. In Sec. IV, a CFD engine is derived from the NPSS engine using the engine dimension and performance parameters from NPSS as guidance. The low-boom redesign of the Mach 1.7 40-PAX concept with the CFD engines is documented in Sec. V. Section VI completes the consistent coupling of the mission analysis, NPSS engine analysis, and low-boom redesign. Conclusions are presented in Sec. VII.

II. CFD Analysis for Conceptual Low-Boom Design

The Euler CFD solver Cart3D [19] is used for all CFD analyses in this paper. An automated meshing process [21] for Cart3D with additional refinements for a CFD engine is used to generate a mesh for the aeropropulsive Cart3D simulation to compute the off-body pressure at three body lengths (3BL) below the aircraft. For off-body pressure calculation using a Cartesian mesh, the aircraft geometry is rotated around the pitch axis so that the shocks below the aircraft on the symmetry plane are approximately parallel to the z-axis of the Cartesian mesh. This results in a mesh of approximately 30 or 200 million cells for off-body pressure calculation of a configuration with flow-through nacelles or CFD engines, respectively. Each mesh has about 275 grid points to define the off-body pressure at 3BL below the aircraft. For visualization of the off-body pressure solution, the Cartesian mesh is rotated to realign the flow direction horizontally. Figure 1 shows a rotated Cartesian mesh on the symmetry plane for off-body pressure calculation. It also highlights the refinement differences of meshes for a flow-through nacelle and a CFD engine.

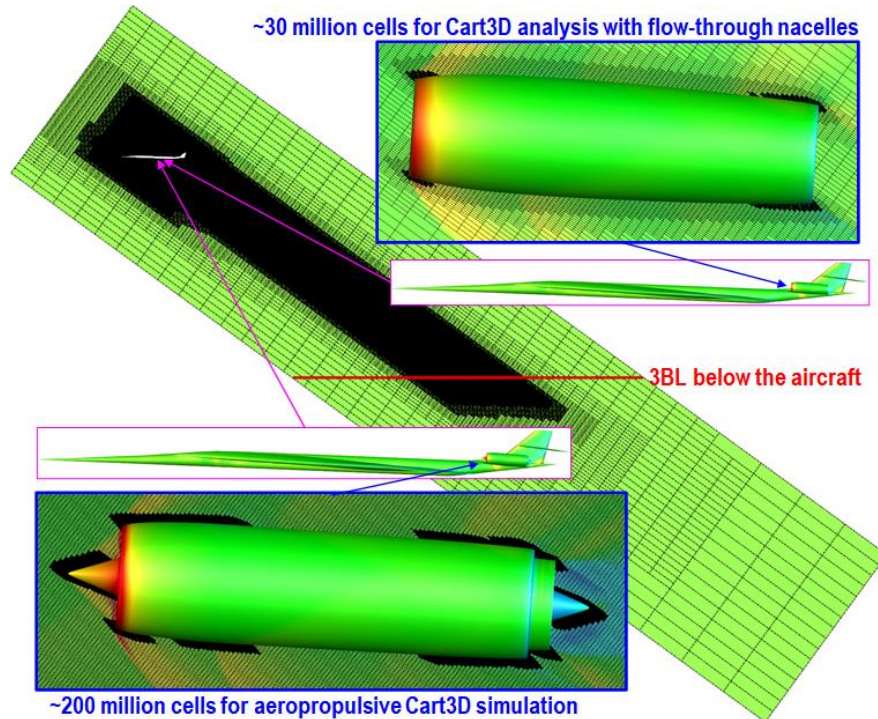


Fig. 1 Cart3D meshes for off-body pressure calculation with CFD engine or flow-through nacelle.

A typical convergence history for off-body pressure calculation using the aeropropulsive Cart3D simulation is shown in Fig. 2a. It takes about 40 hours of wall-clock time to complete 3000 iterations for an aeropropulsive Cart3D simulation using a mesh of about 200 million cells and a Linux server with 96 cores of Intel Xeon CPUs at 2.2 GHz. Figure 2a indicates that the global residual after 3000 iterations is approximately the same as that after 1500 iterations. So, the number of iterations for off-body pressure calculation using the aeropropulsive Cart3D simulation is set at 1500 in this paper, with about 20 hours of wall-clock time per analysis.

For calculation of mass inflow and outflow only, a much smaller Cartesian mesh around the aircraft with additional refinements for a CFD engine is used. This mesh has about 10 million cells. A total of 400 iterations are used for the Cart3D mass flow calculation in this paper, with a typical convergence history in Fig. 2b and a wall-clock time of about 16 min per analysis. The Cart3D analysis with such a mesh is used to ensure that the CFD mass inflow matches the CFD mass outflow, the CFD engine thrust matches the required engine thrust, and the CFD aerodynamic lift matches the cruise weight, before conducting the off-body pressure analysis.

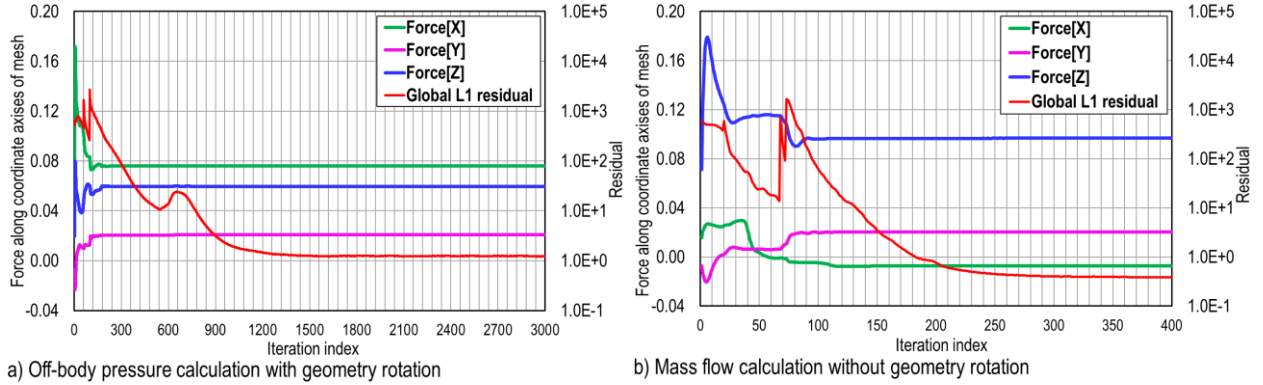


Fig. 2 Typical convergence histories for aeropropulsive Cart3D simulation.

Note that Cart3D has an adjoint-based adaptive mesh refinement method for a numerically more accurate off-body pressure calculation, but it is too expensive for conceptual low-boom design and requires some expertise to use. The meshing approach outlined above allows a robust automation of the Cart3D analysis for conceptual low-boom design, with an adequate accuracy.

III. Low-Boom Concept with Flow-Through Nacelles

A multi-objective MDO problem for development of low-boom supersonic transports was formulated in Ref. [5], which is restated here for easy reference.

$$\begin{aligned}
 & \min_{\mathbf{D}} \{ \text{TOGW}_{\text{OL}}, -R_{\text{OL}} \} \\
 & \text{subject to } \mathbf{l} \leq \mathbf{D} \leq \mathbf{u} \\
 & g_i(\mathbf{D}) \geq 0 \quad (1 \leq i \leq 9) \\
 & \text{CG}_{x,\text{aft}} - \text{CP}_{x,\text{CFD}} \geq 1 \\
 & \|A_{e,r}(\mathbf{D}) - A_{e,r}^{\text{target}}(\mathbf{D})\| \leq \varepsilon \\
 & \text{PLdB}(A_{e,r}^{\text{target}}(\mathbf{D})) \leq 70
 \end{aligned} \tag{1}$$

See Ref. [5] for a detailed explanation of Eq. (1). This MDO problem aims to find a CFD-based low-boom design that satisfies the mission requirements, has the minimum weight, and attains the maximum overland range. The mission requirements are represented by the nine constraints $g_i(\mathbf{D}) \geq 0$, which ensure that the aircraft can (i) carry 40 passengers and have the storage space for the landing gear, (ii) fly overland at cruise Mach 1.7 and cruise altitude H_{OL} (as a design variable), (iii) fly an unrestricted overwater mission with range of 3600 nm at cruise Mach 1.8 and cruise ceiling of 60,000 ft, and (iv) take off and land at airports with the maximum field length of at least 8350 ft. See Ref. [5] for the detailed definitions of these nine constraints. The constraint $\text{CG}_{x,\text{aft}} - \text{CP}_{x,\text{CFD}} \geq 1$ is used to maintain the designed low-boom shape at SOC using fuel redistribution instead of control surface deflections for trim. The low-boom requirement is enforced by two constraints related to $A_{e,r}^{\text{target}}(\mathbf{D})$. Their purpose is to make $A_{e,r}$ of the low-boom concept closely match a low-boom $A_{e,r}$ target with sonic boom ground noise level below 70 PLdB. The choice of 70 PLdB is based on the NASA N+3 low-boom goal [1]. The tolerance ε for the inverse design error is a user-specified positive number

less than 1% of the maximum value of $A_{e,r}^{\text{target}}(\mathbf{D})$. A smaller value of ε makes Eq. (1) more difficult to solve, but the resulting low-boom concept is closer to the ideal low-boom design. A mathematical argument in Ref. [5] shows that the minor mismatches between $A_{e,r}(\mathbf{D})$ and $A_{e,r}^{\text{target}}(\mathbf{D})$ can be reduced with minor OML modifications of the generated low-boom concept. Such a design refinement could reduce the actual ground noise level below 78 PLdB with an existing low-boom shaping method for reduction of the sonic boom ground noise level {see the literature reviews in Ref. [5]}.

An appropriate fidelity strategy is used for the analyses to compute the quantities in Eq. (1). Low-fidelity aerodynamic analyses are used for the mission analysis. This leads to aerodynamics modeling uncertainties in the analysis results, which are manifested as the system-level uncertainties in the aircraft weight, fuel weight, and range. However, the aircraft weight estimation for a low-boom supersonic transport has an unknown uncertainty due to the lack of historical data for validation, even if a finite-element method is used to calibrate the fuselage and wing weight estimates [22]. Replacing low-fidelity aerodynamic analysis by the viscous CFD analysis for the mission analysis is computationally impractical and does not significantly reduce the weight and range uncertainties for the generated low-boom concept. But the consistency between the low-fidelity aerodynamic analysis for the mission analysis and Cart3D for sonic boom analysis is achieved at SOC using a calibrated lift method [5], which enforces the calibrated low-fidelity aerodynamic analysis code LTSTAR [23] to reproduce the same wing lift and total lift as Cart3D for any configuration at SOC. The mission performance data in Eq. (1) are generated using the calibrated low-fidelity aerodynamic analyses, whereas the low-boom constraints in Eq. (1) are computed using Cart3D for the OML of the aircraft with flow-through nacelles.

The Mach 1.7 40-PAX concept (see Fig. 3) is a solution of Eq. (1) generated using the BCO method [5]. The fuselage volume requirements for 40 passengers and storage of the landing gear are formulated as one of the nine mission constraints in Eq. (1). This constraint was considered to be satisfied with an empirical estimate in Ref. [5]. A more detailed and realistic cabin layout is provided in this paper to show that the fuselage volume requirements are satisfied (see Fig. 4). The seat pitch is reduced from 48 inches for the low-boom concept in Ref. [5] to 46 inches due to the required spaces for two lavatories. The seat pitch and aisle width in Fig. 4 are more spacious than the economy class seating for a Gulfstream low-boom concept in Ref. [24]. The overland and overwater mission profiles are defined in Fig. 5. Table 1 includes some weight and performance data of the Mach 1.7 40-PAX concept using the Flight Optimization System (FLOPS) [25] for mission analysis. The ranges from the mission analysis are marginally longer than those in Ref. [5] due to more careful choices of the input parameters for the mission analysis. For example, only one flight attendant (see Fig. 3) is required based on 14 CFR §91.533 of the Federal Aviation Regulations [26], while two attendants were used for mission analysis in Ref. [5]. See Ref. [5] for a detailed description of the analysis methods used in the FLOPS mission analysis.

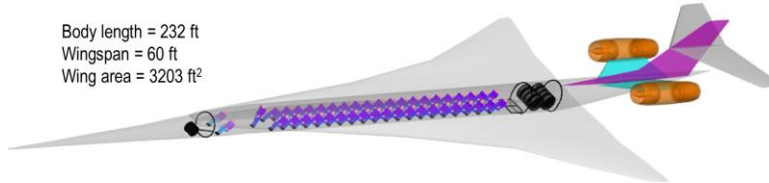


Fig. 3 Mach 1.7 40-PAX concept.

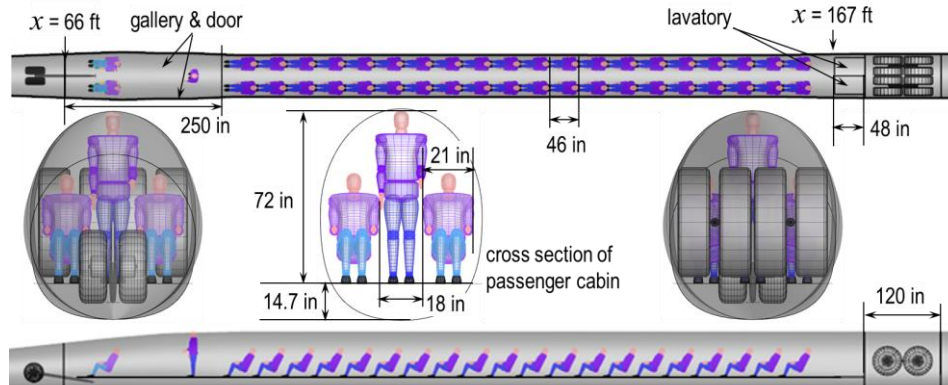


Fig. 4 Detailed cabin layout of Mach 1.7 40-PAX concept.

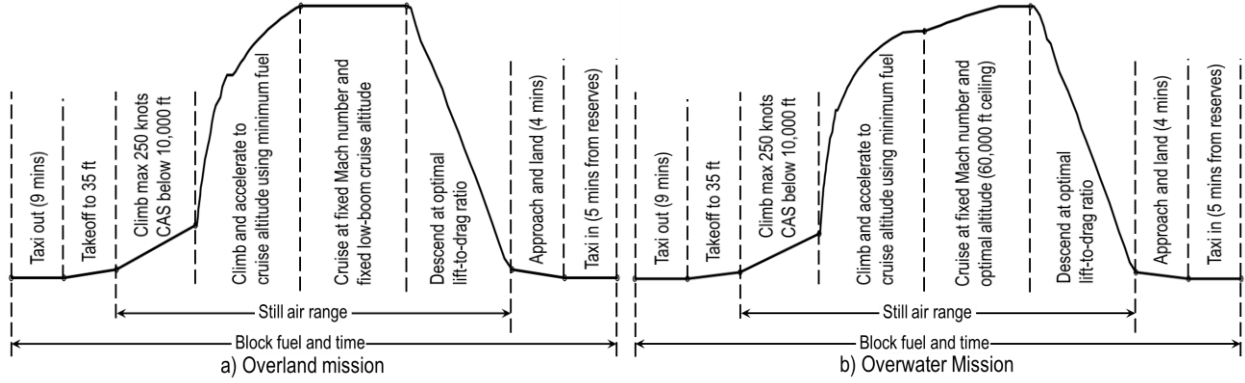


Fig. 5 Overland and overwater mission profiles.

Table 1 Mach 1.7 40-PAX concept

Variable	Value	Variable	Value
Seat pitch, in	46	Low-boom angle of attack, deg	2.30
MTOGW, lb	144,251	Altitude at start of overland cruise, ft	52,240
Zero fuel weight, lb	70,642	PLdB of low-boom inverse design target	69.9
Overwater cruise Mach	1.8	Weight at start of overland cruise, lb	133,594
Overland cruise Mach	1.7	Block fuel for maximum range, lb	64,655
Takeoff field length, ft	8320	Overwater range, nm	3921
Approach velocity, kts	136	Overland range, nm	3527

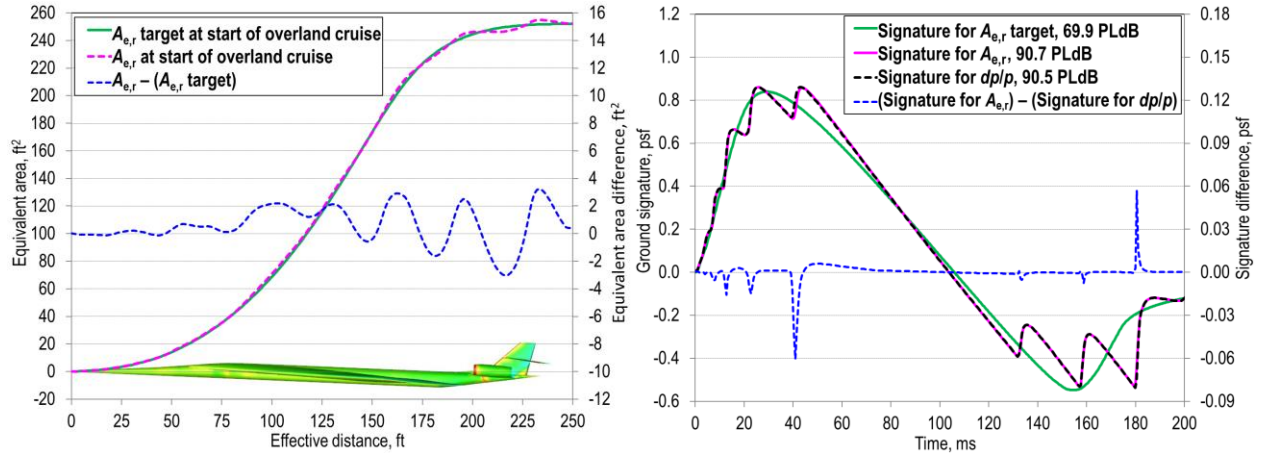


Fig. 6 Equivalent areas and undertrack ground signatures at SOC.

The Mach 1.7 40-PAX concept is an acceptable CFD-based low-boom inverse design for a given $A_{e,r}$ target of 69.9 PLdB and has the potential to achieve an undertrack sonic boom ground noise level below 70 PLdB at SOC (see Fig. 6). The notional NPSS engines in Fig. 3 are modeled as flow-through nacelles for CFD analysis. The $A_{e,r}$ is obtained by using a reverse propagation of dp/p at 3BL below the aircraft to 50 ft below the aircraft and converting the reversely propagated overpressure to an equivalent area [20]. The ground signature for any A_e is obtained by converting A_e to an F-function, scaling the F-function to get the off-body pressure at 50 ft below the cruise altitude (of 52,240 ft), and using an augmented Burgers equation to propagate the off-body pressure to the ground through the standard atmosphere [27]. See sec. II.F in Ref. [5] for the involved formulas. The humidity profile for the standard atmosphere is based on ANSI S1.26 [28]. The PLdB value of a ground signature is computed using the method in Ref. [2]. This sonic boom analysis method for $A_{e,r}$ is nearly equivalent to the state-of-the-art sonic boom analysis method [4,29], which computes the undertrack ground signature using the augmented Burgers equation for propagation of dp/p at 3BL below the aircraft to the ground. As shown in the signature plot of Fig. 6, the undertrack ground signature for $A_{e,r}$

is almost identical to that for dp/p at 3BL below the aircraft. This confirms that designing a low-boom configuration using the CFD dp/p for sonic boom analysis is approximately equivalent to designing a configuration with a low-boom $A_{e,r}$ shape. The undertrack ground noise level for the target signature is 69.9 PLdB, which ensures theoretically that a perfect match of the configuration's $A_{e,r}$ with the $A_{e,r}$ target will achieve the goal of having an undertrack sonic boom ground noise level below 70 PLdB. Note that $A_{e,r}$ and the undertrack ground signature of the Mach 1.7 40-PAX concept are slightly different from those in Ref. [5], even though the same OpenVSP [30] geometry is used for the CFD-based sonic boom analyses. The differences are mainly caused by a more refined point representation of the OpenVSP geometry for the Cart3D analysis in this paper.

IV. Approximation of NPSS Engine by CFD Engine

Wintzer, Ordaz, and Fenbert [12] showed that the engine plume could have a detrimental effect on the undertrack ground signature of a low-boom flight demonstrator designed using a flow-through nacelle as the engine model for Cart3D analysis of the full vehicle. So, a major concern for the Mach 1.7 40-PAX concept is whether an aeropropulsive Cart3D simulation for the full vehicle would have a detrimental effect on its low-boom $A_{e,r}$ shape, which defines the low-boom requirement in Eq. (1). Moreover, if the aeropropulsive Cart3D simulation is required to compute the off-body pressure for sonic boom analysis, which improves the analysis fidelity of Eq. (1), could Eq. (1) still be solved consistently for all the disciplines? In the remainder of this paper, we use the Mach 1.7 40-PAX concept as the baseline to demonstrate how Eq. (1) can be solved consistently using the aeropropulsive Cart3D simulation of the full vehicle for sonic boom analysis.

A powered engine is typically simulated using a CFD engine with inflow and outflow BCs in CFD analysis, even though other methods are also used (such as an actuator disk approach [18]). The CFD engine in Fig. 7 aims to simulate the VCE for the Mach 1.7 40-PAX concept. The sketch of the VCE in Fig. 7 is an aero-mechanical flow-path diagram with the exact number of fan/compressor/turbine stages. The VCE model is a one-dimensional analysis that includes inlet total pressure recovery (inlet PR) and installation effects [6]. It was evolved from the NASA F404 NPSS model {see sec. III.C of Ref. [13]} and has the bypass nozzle for acoustic shielding. Note that the flow from the bypass nozzle was called the tertiary flow in Ref. [6]. The sea-level static thrust of the VCE is used as the sizing design variable for solving Eq. (1). The size, weight, and performance data of the VCE are scaled using the sea-level static thrust. For the low-boom MDO problem [Eq. (1)], the VCE was optimized using the sea-level static thrust for minimum $TOGW_{OL}$ in Ref. [5]. This section documents a consistent coupling approach for NPSS and Cart3D analyses by constructing a CFD engine as an approximation of the VCE for the aeropropulsive Cart3D simulation, which is a novel approach for the propulsion-airframe integration.

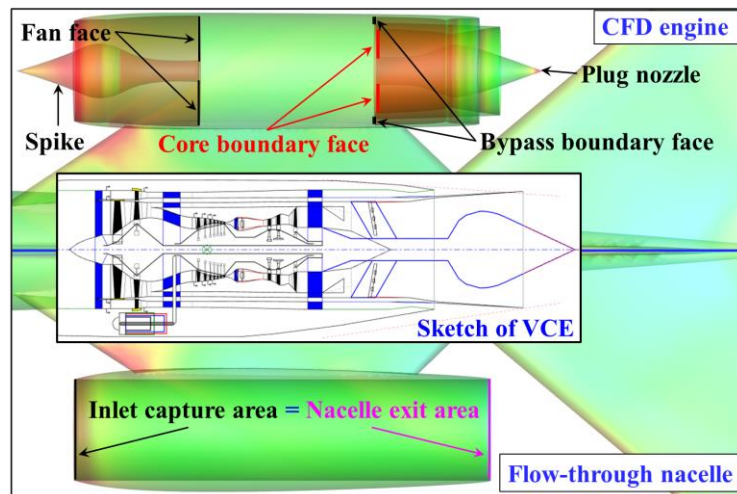
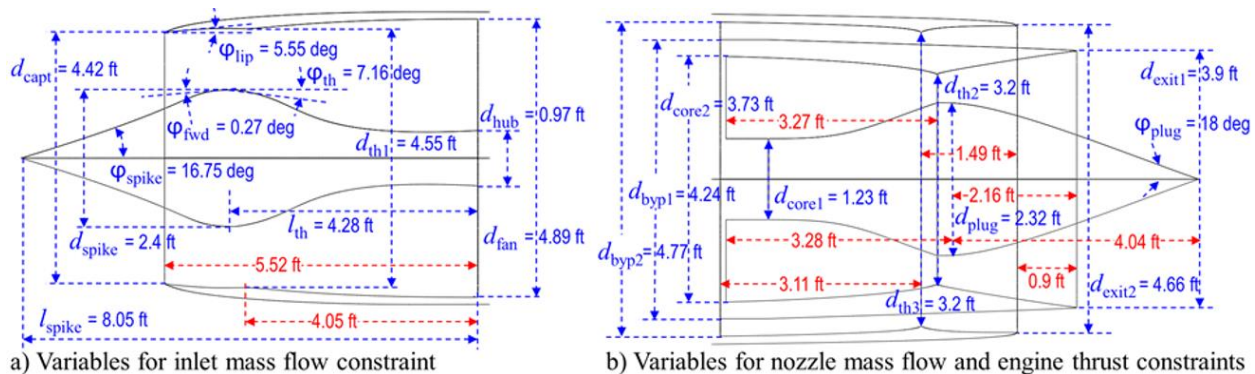


Fig. 7 CFD engine and flow-through nacelle for modeling the VCE on the Mach 1.7 40-PAX concept.

The VCE has a nozzle with variable throat and exit areas to achieve optimal performance for the required thrust at each operating condition, while the CFD engine has a fixed shape for sonic boom analysis at SOC. So, the CFD engine approximation depends on the operating condition of the VCE at SOC. The VCE has the performance data (such as the pressure and temperature) at the boundary faces of the CFD engine for each operating condition. The coupling between the VCE and the CFD engine approximation in this paper strives to achieve the following two consistency

goals: (i) the mass flow and thrust of the CFD engine are approximately the same as those of the VCE at SOC and (ii) the nozzle BCs used by the aeropropulsive Cart3D simulation are identical to those derived from the VCE performance data for SOC.

The process for approximation of an NPSS engine at SOC by a CFD engine can be briefly summarized by the following eight steps.



Before discussing the eight steps of the above approximation process, we give a brief overview of their purposes. The most difficult part of the CFD engine approximation of an NPSS engine is the construction of an initial CFD engine with a proper r_{sp} at the fan face that has the desired engine flow characteristics using the aeropropulsive Cart3D simulation. Here the desired engine flow characteristics are determined conceptually (see Fig. 9): as the flow goes through the engine, the inlet flow speed is reduced from supersonic to subsonic and the exit flow speed is increased from subsonic to supersonic. In theory, under the same flight condition, the engine inlet can operate normally for an

appropriate range of r_{sp} . However, the inlet could have an abnormal flow condition that cannot be simulated by the aeropropulsive Cart3D simulation. One abnormal inlet flow condition is when the inlet goes into buzz at mass flows well below that needed for normal engine operation [32]. So, Steps 1 to 5 of the approximation process are used to define an initial CFD engine and a range of r_{sp} such that a consistent CFD engine approximation is attainable for some r_{sp} in the selected range and a minor modification of the initial CFD engine. Then, small ranges for the design variables can be used to find a desired CFD engine approximation. If the ranges of the design variables are not properly controlled, there might be many failed aeropropulsive Cart3D runs during optimization, which might not yield any useful information for defining a design space that contains a feasible solution. Steps 1 to 5 ensure that Steps 6 and 7 will not become a never-ending trial-and-error process for solving the inlet and nozzle shape optimization problems because of a lack of knowledge about the appropriate ranges for the design variables. Step 8 simulates how the VCE works if the required thrust is changed while the cruise Mach and altitude at SOC are fixed. This step is only required if the low-boom shaping changes the aircraft OML significantly and results in a significant change of the aircraft drag at SOC. In this paper, the required mass flow of the VCE at SOC does not change because of the fixed cruise Mach and altitude. There is no change to the inlet flow condition for the CFD engine with respect to a change of the aircraft OML (excluding the CFD engines) aft of the inlet. So, a thrust change of the VCE at SOC can be simulated by changing the nozzle throat areas of the CFD engine, which is Step 8. Overall, once a good baseline for the CFD engine approximation is available, it is not too difficult to get a desired CFD engine approximation. Once a desired CFD engine approximation is obtained, it is extremely easy to modify the CFD engine for different thrust requirements if needed.

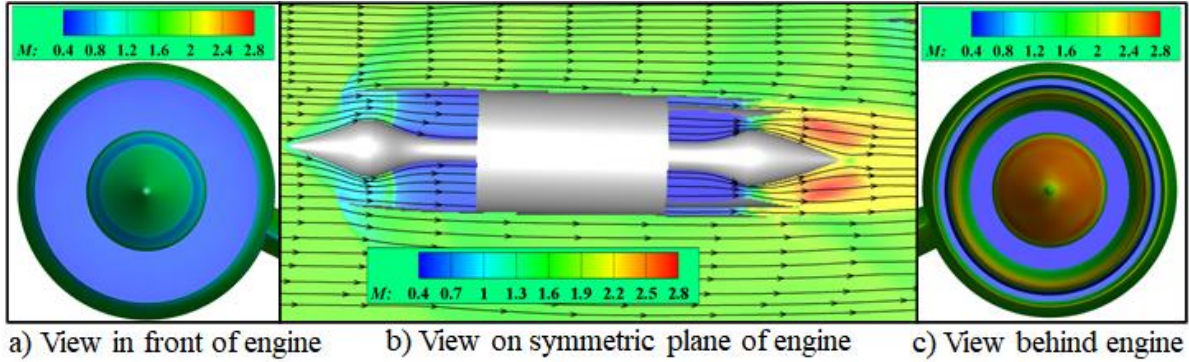


Fig. 9 Mach contours and streamlines around the CFD engine on the Mach 1.7 40-PAX concept.

The first step in the approximation process requires some knowledge about supersonic inlet and nozzles to construct the parametric OpenVSP geometry illustrated in Fig. 8. OpenVSP uses a blending surface to connect two defined cross section shapes. If needed, one could specify two angle parameters to determine the longitudinal slopes of the blending surface at the two end cross sections (such as ϕ_{spike} and ϕ_{fwd} in Fig. 8a). The OpenVSP parameters for the CFD engine shape in Fig. 8 are adequate for approximation of the VCE at SOC.

Step 2 is a manual process of finding the relevant engine dimension and performance data at SOC. Three sets of BCs for the VCE at SOC are extracted from the NPSS analysis data: (i) r_{sp} of 4.06 for inflow at the fan face, (ii) a total pressure ratio of 3.04 and a total temperature ratio of 2.69 for outflow at the core boundary face, and (iii) a total pressure ratio of 1.53 and a total temperature ratio of 1.18 for outflow at the bypass boundary face. The VCE thrust at SOC is 8,640 lb. The VCE dimension parameters at SOC are collected from the WATE++ [33] analysis data, which is integrated with NPSS Version 2.6, the version used for the NPSS engine analysis in this paper.

Step 3 uses SUPIN to design the inlet (including the spike) and nacelle OML up to the fan face. SUPIN is capable of generating an inlet shape for CFD analysis [31]. The key input parameters for SUPIN include (i) the cruise Mach of 1.7 and altitude of 52,240 ft at SOC as the freestream flight condition for the inlet, and (ii) the fan-face dimension parameters and the mass inflow at the fan face for SOC from NPSS. See sec. II.C of Ref. [31] for details. This step is independently performed using SUPIN.

Next, a notional NPSS engine geometry (see Fig. 10) is constructed using the VCE dimension parameters at SOC as guidance. The notional NPSS engine geometry has the same inlet capture area, nozzle throat areas, and dimension parameters for the boundary faces as those of the VCE at SOC. But some shape parameters (such as the nacelle diameters) are determined empirically due to a lack of the geometry details for the VCE nacelle. This notional NPSS engine was used in Ref. [5] to construct the flow-through nacelle of the Mach 1.7 40-PAX concept after adjusting the inlet capture area to be the same as the nacelle exit area (see Fig. 7). In general, for modeling an NPSS engine as a

flow-through nacelle consistently, such a notational NPSS engine shape is required. Then, an initial CFD engine is constructed using the parametric inlet/nozzle geometry in Fig. 8. The construction is a manual process of adjusting the 21 parameters in Fig. 8 and one cross section diameter of the nacelle at the fan face location to match the front part of the CFD engine with the generated SUPIN inlet/nacelle and the aft part of the CFD engine with the notational NPSS engine. The red length values in Fig. 8 are either based on the VCE dimension data or empirical. This completes Step 4 of the approximation process.

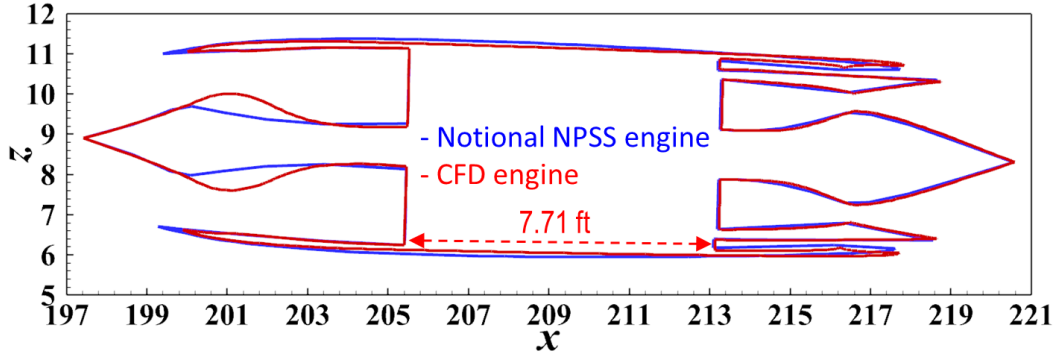


Fig. 10 Notional NPSS engine to define the flow-through nacelle and its CFD engine approximation.

Step 5 finds the initial range of r_{sp} for Step 6. The nozzle BCs of the VCE obtained in Step 2 are applied to the CFD engine for the aeropropulsive Cart3D simulation. The theoretical justification for this step is to determine a range of r_{sp} for the actual flight condition of the installed CFD engine that does not lead to any abnormal inlet flow condition. To illustrate the necessity of changing the inflow BC of the VCE for the aeropropulsive Cart3D simulation, the aeropropulsive Cart3D simulation is performed using r_{sp} (4.06) of the VCE at SOC as the BC at the fan face of the CFD engine. The global residual for the Cart3D solution is dropped by 2.4 orders of magnitude after 400 iterations. Figure 11 is a Mach contour plot on the symmetry plane of the engine for this Cart3D solution. It has some reversed flow streamlines inside the inlet. The computed mass inflow of 25.7 lb/s at the fan face is about 10% of the computed mass outflow of 246.7 lb/s at the nozzle boundary faces, which indicates an abnormal inlet flow condition. A more advanced aeropropulsive simulation might show some unsteady nature of the inlet flow {see fig. 1 in Ref. [32]} when r_{sp} at the fan face is too high.

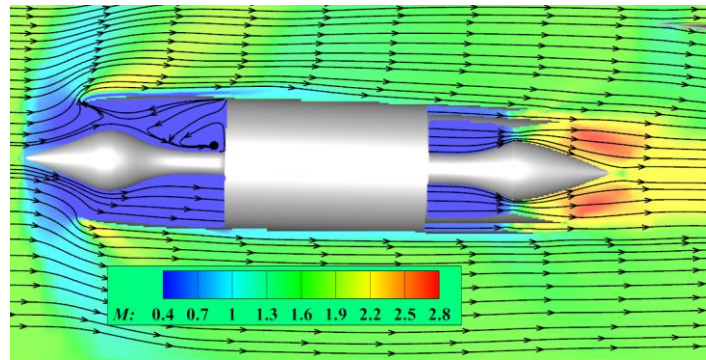


Fig. 11 Mach contours and streamlines around the CFD engine with a non-compatible inflow BC.

Step 5 is implemented using the parametric study tool in ModelCenter [34]. ModelCenter is used to integrate OpenVSP and Cart3D, as well as other analysis tools {see Ref. [5]}, for the aeropropulsive Cart3D simulation of the full vehicle using the parametric CFD engine in Fig. 8. When the CFD engine has the desired engine flow characteristics (see Fig. 9), the mass flow at the fan face deviates slightly from a constant value and the inlet PR is an increasing function of r_{sp} (see Fig. 12). However, if r_{sp} exceeds a limit, both the mass flow and the inlet PR decrease drastically, indicating some abnormal flow condition in the inlet (see Figs. 11 and 12). The selected range of r_{sp} for Step 6 is [3.35, 3.9] based on the parametric study result in Fig. 12. Note that this step is only to determine an initial range of r_{sp} for Step 6. The specified conditions for selecting the range of r_{sp} are empirical and could be replaced by different conditions if needed.

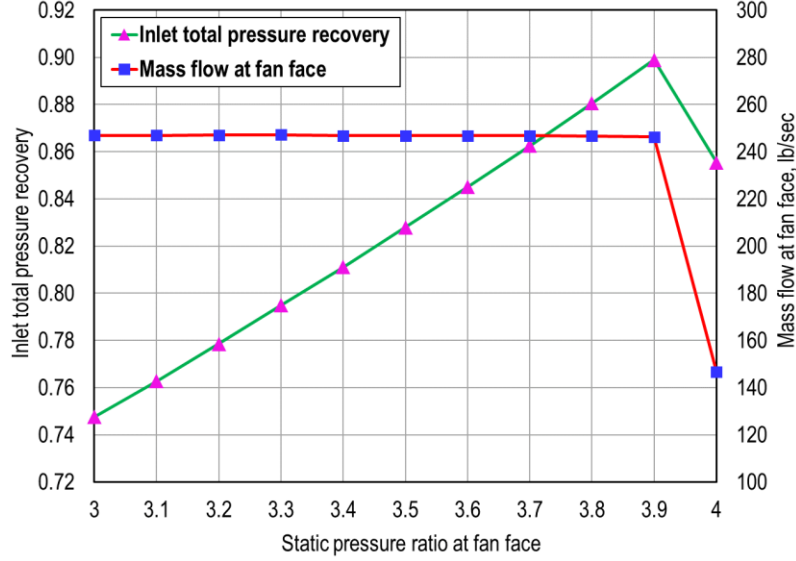


Fig. 12 Parametric study of inlet PR and mass flow with respect to r_{sp} .

Step 6 is an optimization problem to maximize the inlet PR and satisfy the inlet mass flow constraint. The eleven blue variables in Fig. 8a and r_{sp} are used as the design variables for optimization. The corresponding optimization problem has the inlet PR as the objective function and $|(mass\ inflow\ of\ CFD\ engine) - (mass\ inflow\ of\ VCE\ at\ SOC)| / (mass\ inflow\ of\ VCE\ at\ SOC) \leq 2\%$ as the constraint. The solution of Step 6 is generated using the Design Explorer (a derivative-free optimizer) in ModelCenter. Note that some CFD solvers [35,36] can use a specified mass inflow to define the BC at the fan face. Such a capability can eliminate the static pressure ratio as a design variable, which will eliminate Step 5 and simplify Step 6 of the approximation process. However, the current version of Cart3D [19] does not have the option of using the mass inflow as the BC at the fan face.

Step 7 enforces the mass outflow and engine thrust constraints. It is formulated as an optimization problem with one objective, one constraint, and the ten blue variables in Fig. 8b as design variables. The objective is the relative error of the thrust constraint, defined as $|(CFD\ engine\ thrust) - (VCE\ thrust\ at\ SOC)| / (VCE\ thrust\ at\ SOC)$. The constraint uses a tolerance of 2% for the match of mass flows, defined as $|(mass\ outflow\ of\ CFD\ engine) - (mass\ outflow\ of\ VCE\ at\ SOC)| / (mass\ outflow\ of\ VCE\ at\ SOC) \leq 2\%$. This optimization problem is also solved using the Design Explorer in ModelCenter. The optimization iteration is terminated once the objective function value is less than 1% and the mass flow constraint is satisfied. In Steps 6 and 7, the design variables related to the dimension parameters of the VCE are constrained with lower and upper bounds so that the optimized engine is reasonably close to the VCE in terms of approximation errors of dimension parameters.

It is worth mentioning that Steps 6 and 7 were completed with multiple optimization runs to obtain the CFD engine for the Mach 1.7 40-PAX concept. Each step went through an interactive iteration process by selecting a group of design variables and their bounds for optimization to search for a feasible solution. Such interactive optimization runs are necessary for engineering optimization problems with an unknown design space that contains a desired solution {see the blue iteration loop in fig. 1 of Ref. [37]}. Once the specified design space contains a feasible solution for the mass flow and thrust constraints, the optimal solutions can be found easily. The values for lengths, diameters, and angles in Figs. 8 and 10 can be used to reproduce the CFD engine generated by the approximation process.

Step 8 is used to readjust the CFD engine approximation of the VCE at SOC for a different engine thrust if a cyclic iteration process is required to achieve the coupling consistency between the mission analysis, NPSS engine analysis, and low-boom redesign using the aeropropulsive Cart3D simulation. The cruise Mach and altitude are fixed in this paper. The operating condition of the VCE at SOC is determined by the required engine thrust, which could change if the aircraft OML is changed. Even though Step 8 is not used for the low-boom redesign study documented in this paper, it was used successfully for similar studies with other CFD engine approximations during our numerical experiments for development of the CFD engine approximation process.

The Mach contours of the CFD engine approximation of the VCE at SOC are plotted in Fig. 9. The average Mach numbers are 0.467, 0.455, and 0.233 at the fan face, bypass boundary face, and core boundary face of the CFD engine, respectively. Because the VCE is a one-dimensional model in freestream conditions in NPSS, the actual Mach numbers in the VCE model at these boundary faces are likely different and would account for some of the differences

in the areas in Table 2. This does not have a significant impact on the overall performance or plume of the VCE. The inlet PR for the CFD engine is about 90%. Figure 10 compares the shapes of the notional VCE geometry at SOC and the CFD engine for the Mach 1.7 40-PAX concept. It shows that the two engines are very similar in terms of overall sizes. Table 2 compares some dimension and performance parameters of the VCE at SOC and the CFD engine. The nine coupling variables of the CFD engine are very close to those of the VCE, with a maximum relative difference of 1.7%. The geometry equality constraints were imposed for the areas of the core boundary face and fan face during the earlier trials, but the geometry equality constraint for the area of the fan face was relaxed by a relative error tolerance of 1.1% for the final CFD engine approximation. The noticeable differences of 4.9% to 17.1% of the five non-coupling variables in Table 2 are needed for the CFD engine to satisfy the mass flow constraints and match the VCE thrust at SOC. The reason to list the non-coupling variables in Table 2 is to point out that, even though the coupling consistency between the NPSS engine analysis and the aeropropulsive Cart3D simulation is achieved for the engine plume simulation in this paper, further studies are required to improve the coupling consistency for engine performance analysis, which is beyond the scope of this paper.

Table 2 Parameters for the VCE and its CFD engine approximation

Coupling variable	VCE	CFD	Relative difference
Thrust, lb	8640.5	8580.6	0.9%
Mass inflow at fan face, lb/s	243.0	246.6	1.5%
Mass outflow of nozzles, lb/s	242.5	246.7	1.7%
Total pressure ratio for core BC	3.04	3.04	0.0%
Total temperature ratio for core BC	2.69	2.69	0.0%
Total pressure ratio for bypass BC	1.53	1.53	0.0%
Total temperature ratio for bypass BC	1.18	1.18	0.0%
Area of core boundary face, in ²	1402.2	1402.0	0.0%
Area of fan face, in ²	2571.4	2599.4	1.1%
Non-coupling variable	VCE	CFD	Relative difference
Throat area of core nozzle, in ²	577.8	549.3	4.9%
Inlet capture area, in ²	2079.4	2213.3	6.4%
Static pressure ratio for fan-face BC	4.06	3.57	12.1%
Throat area of bypass nozzle, in ²	329.4	371.8	12.9%
Area of bypass boundary face, in ²	464.8	544.3	17.1%

V. Low-Boom Redesign Using Aeropropulsive CFD Simulation

The computational cost of obtaining a supersonic configuration with undertrack sonic boom ground noise level around 76 PLdB is very high because hundreds of CFD off-body pressure analyses with adjoint solutions are required for shaping the undertrack ground signature into a similar smooth shape as the target signature, which is the only known method to obtain an undertrack sonic boom ground noise level around 76 PLdB [12]. There is no guarantee that such a configuration could be obtained for the required lift coefficient even with flow-through nacelles [12]. So, the low-boom redesign using the aeropropulsive CFD simulation in this paper seeks an acceptable low-boom inverse design for an $A_{e,r}$ target with an undertrack ground noise level below 70 PLdB [see Eq. (1)]. In other words, the low-boom redesign using the aeropropulsive CFD simulation is to approximately recover the low-boom $A_{e,r}$ shape in Fig. 6 for a low-boom concept with the CFD engines. A detailed shaping to further reduce the undertrack ground noise level can be conducted in a later design phase if needed, knowing that only minor volume and lift distribution modifications are required {see the introduction of Ref. [5]} to obtain a low-boom shape with an undertrack sonic boom noise level around 76 PLdB using an adjoint-based low-boom shaping method [12].

With an acceptable low-boom $A_{e,r}$ shape as the goal, the low-boom redesign using the aeropropulsive Cart3D simulation becomes much simpler, at least for the Mach 1.7 40-PAX concept. Only two design variables are enough to tailor the aft $A_{e,r}$ shape to obtain an acceptable low-boom $A_{e,r}$ shape for a concept with the CFD engines. The coupling of the low-boom redesign using the aeropropulsive Cart3D simulation and FLOPS mission analysis will be discussed in the next section.

One important constraint for the engine is that the incident angle of the engine with respect to the fuselage must be exactly the same as that of the flow-through nacelle, because this angle has a significant effect on the aft ground signature shape. The Mach 1.7 40-PAX concept with the flow-through nacelles has an optimal incident angle of 1.466 deg for low-boom aft shaping. So, the engine for the Mach 1.7 40-PAX concept is constrained to a fixed incident angle of 1.466 deg. This constraint ensures that the aft signature shape change of the concept with CFD engines is not affected by the engine incident angle. Empirical evidence indicates that the aft low-boom $A_{e,r}$ shape is minimally distorted under this constraint. For example, an early redesign attempt using the incident angle constraint was successfully completed with only minor changes of the pylon twist angle and tail deflection angle. In contrast, another attempt of redesigning the Mach 1.7 40-PAX concept used a CFD engine at an incident angle of zero deg. This led to significant aft OML modifications using four additional design variables, including the twist angle of the wing tip airfoil and two shape parameters of two fuselage cross sections, to obtain a low-boom concept with the CFD engines.

For convenience, the Mach 1.7 40-PAX concept with the flow-through nacelles will be called the flow-through concept. Any configuration with the CFD engines will be called a powered concept. The tail deflection angle of the Mach 1.7 40-PAX concept with the CFD engines is adjusted for the lift match. The tail deflection angle is changed from 4.57 deg for the flow-through concept to 4.70 deg for this powered concept so that the aerodynamic lift coefficients of these two concepts have the same value of 0.0942. This powered concept with the tail deflection angle of 4.70 deg will be called the initial powered concept. The inverse design optimization goal for the initial powered concept is to increase the values of $A_{e,r}$ for x_e between 205 and 225 ft (see Fig. 13a), which can be achieved by modifying the OML of the aircraft between the corresponding Mach angle cut planes (see the colored planes in the geometry insert of Fig. 13a). Based on the geometry insert of Fig. 13a, we know that the pylon lift distribution can be used to modify $A_{e,CFD}$ to reduce the $A_{e,r}$ matching error around $x_e = 215$ ft {see eq. (1) in Ref. [5]}. So, the pylon twist angle is used for a better match of the aft $A_{e,r}$ of the powered concept with the $A_{e,r}$ target and the tail deflection angle is used to maintain the required lift for the powered concept. Due to high computational costs for off-body pressure calculation using the aeropropulsive Cart3D simulation (see Sec. II), a parametric study for the pylon twist angle with step size of 0.5 deg is used for finding a powered concept that satisfies the $A_{e,r}$ matching error constraint in Eq. (1), followed by enforcing $C_L = 0.0942$ with the tail deflection angle as the design variable using the aeropropulsive Cart3D simulation for the surface pressure solution. The lift matching problem is solved using a linear prediction method for the required tail deflection angle based on Cart3D surface solutions for two different tail deflection angles. The required tail deflection angle can be obtained very accurately with three or four Cart3D surface solutions. If the resulting solution were not an acceptable inverse design, then the step size and range for the pylon twist angle would be reduced for a more refined search of an acceptable inverse design. If a refined search were unable to generate an acceptable inverse design, then more design variables would be selected for inverse design optimization and the mixed-fidelity low-boom shaping method [38,39] would be used for reduction of the $A_{e,r}$ matching error, followed by a tail deflection angle adjustment to match the required lift. If needed, the two solution procedures for reducing the $A_{e,r}$ matching error and satisfying the lift constraint are iterated until the generated configuration satisfies both the $A_{e,r}$ matching error constraint in Eq. (1) and the lift constraint. This is a general method for solving the low-boom inverse design optimization problem with the lift constraint. This method was used successfully to solve the low-boom redesign problem in an earlier attempt mentioned above, when five design variables were needed to enforce the $A_{e,r}$ matching error constraint in Eq. (1) for a CFD engine at an incident angle of zero deg with respect to the fuselage.

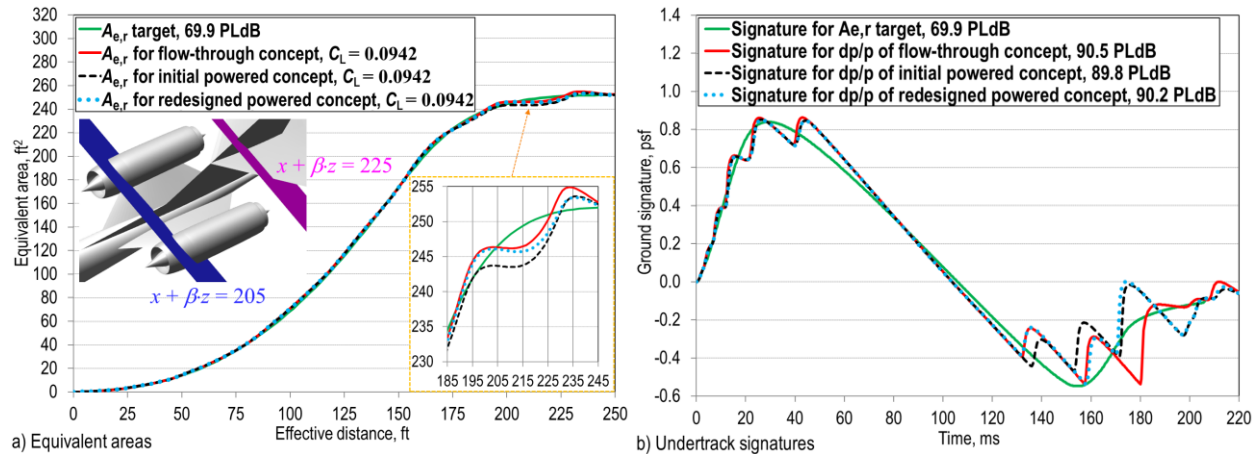


Fig. 13 Equivalent areas and ground signatures for flow-through and powered concepts.

The redesigned powered concept is obtained by changing the pylon twist angle from 0 to 1.0 deg and the tail deflection angle from 4.70 to 4.57 deg. The $A_{e,r}$ of the redesigned powered concept matches the $A_{e,r}$ target closer than that of the initial powered concept (see Fig. 13a). The redesigned powered concept also improves the aft signature match of the initial powered concept with the signature for the $A_{e,r}$ target around 160 ms (see Fig. 13b). The flow-through and redesigned powered concepts differ only by the pylon twist angles and how the NPSS engine is modeled for CFD analysis. They have the same tail deflection angle for matching the total lift with the cruise weight. The aeropropulsive Cart3D simulation does have significant influences on the aft shapes of the dp/p and ground signature (see Figs. 13b and 14), but its effects on the $A_{e,r}$ shape and the PLdB value of the undertrack ground signature are negligible (see Fig. 13). Both the initial and redesigned powered concepts can be considered as acceptable low-boom inverse design solutions for the $A_{e,r}$ target of 69.9 PLdB.

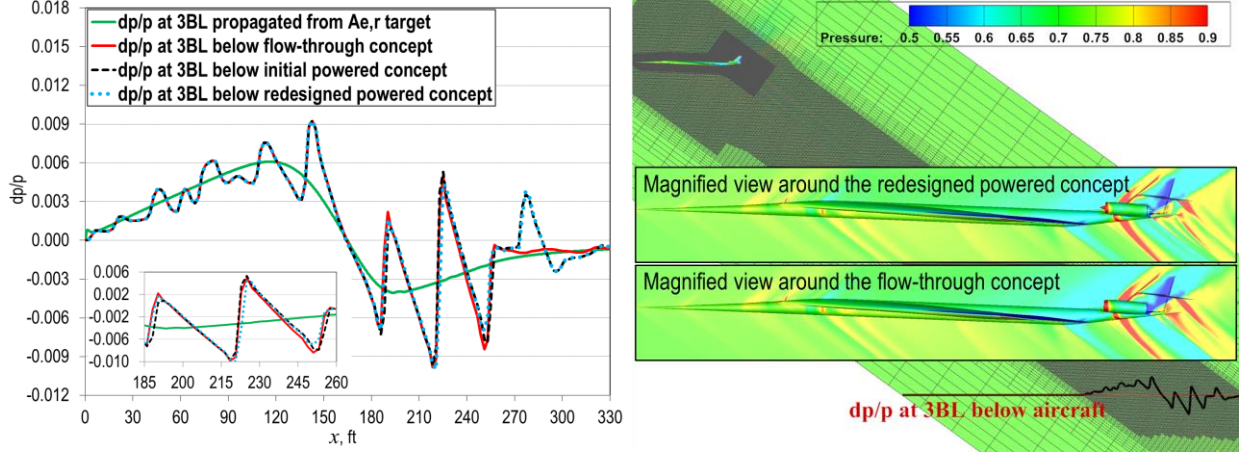


Fig. 14 Off-body pressures for flow-through and powered concepts.

In comparison of the initial and redesigned powered concepts, even though the redesigned powered concept has a slightly higher noise level for its undertrack ground signature, it is still considered to be more desirable at the conceptual design phase because its $A_{e,r}$ is closer to the target, which means that the redesigned powered concept is closer to the ideal low-boom concept with an undertrack ground noise level below 70 PLdB when the difference between their $A_{e,CFD}$ distributions is used as the distance metric {see the introduction of Ref. [5]}.

The simplistic low-boom reshaping to generate the redesigned powered concept in this paper gives a false impression that the inverse design optimization of $A_{e,r}$ with the lift constraint is easy to solve. In theory, it is very difficult to know a priori how to define a low-boom target that can be matched by an inverse design with the required lift. If the $A_{e,r}$ target were not defined properly, the iterative process between the reduction of the $A_{e,r}$ matching error and lift matching would never converge. The low-boom $A_{e,r}$ target in Fig. 13a was generated {see eqs. (8a) and (9) in Ref. [5]} using an intrinsic relation between the cruise weight and $A_{e,r}(l_e)$ of the aircraft {see eq. (11) and its discussion in Ref. [40]}. The redesigned powered concept with the required C_L of 0.0942 further demonstrates the validity of the theory in Ref. [40] on how to generate an $A_{e,r}$ target that can be approximately matched by an inverse design with the required lift, even if the aeropropulsive Cart3D simulation is required for sonic boom analysis.

VI. Coupling of Aeropropulsive CFD Simulation and Mission Analysis

Recall that the FLOPS mission analysis of the Mach 1.7 40-PAX concept uses a calibrated lift method [5] based on the CFD analysis data of the Mach 1.7 40-PAX concept with the flow-through nacelles. So, the mission analysis is not consistent with the CFD simulation data for the redesigned powered concept. This section shows how to achieve a coupling consistency between the FLOPS mission analysis and sonic boom analysis using the aeropropulsive Cart3D simulation. The goal is to perform the sonic boom analysis using the aeropropulsive CFD simulation at SOC determined by the mission analysis, while the mission analysis uses the aerodynamic analyses calibrated by the aeropropulsive CFD simulation data. The cyclic dependency is resolved using an iteration method illustrated by the flowchart in Fig. 15.

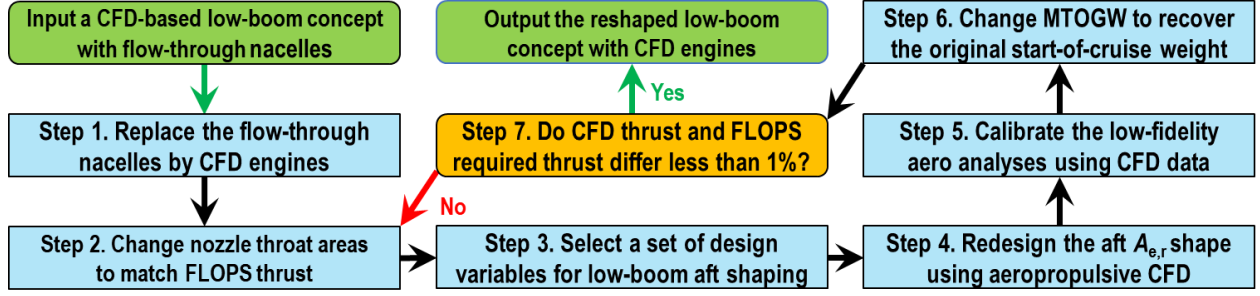


Fig. 15 Integration of mission analysis with low-boom redesign using aeropropulsive CFD simulation.

The iteration method in Fig. 15 can be considered as an extension of the BCO method in Ref. [5], which solves Eq. (1) using a flow-through nacelle as the approximation of the VCE for the full-vehicle CFD analysis. This extension leads to a BCO method for solving Eq. (1) when the VCE is modeled as a CFD engine for the full-vehicle CFD analysis. In other words, when the aeropropulsive Cart3D simulation is used to compute $A_{e,r}(\mathbf{D})$ in Eq. (1), Eq. (1) can still be solved using the BCO method in Ref. [5] to find a CFD-based low-boom concept with flow-through nacelles, followed by the iteration process in Fig. 15 to find a CFD-based low-boom concept with CFD engines. The multidisciplinary coupling scope for the resulting MDO method includes the FLOPS mission analysis, NPSS engine analysis, and low-boom shaping of an aircraft concept using the aeropropulsive Cart3D simulation.

Recall that the FLOPS mission analysis and NPSS engine analysis use a multidisciplinary feasible (MDF) architecture [41] for MDO with the sea-level static thrust of the VCE as the coupling variable {see Ref. [5]}. Although the MDO architecture [41] was introduced for classification of MDO methods, it is used here to describe the coupling relations among the disciplinary analyses in the BCO method for solving Eq. (1). The aeropropulsive CFD simulation and NPSS engine analysis use an MDF architecture with nine coupling variables (see Table 2) for the engine plume simulation. The cyclic dependency between the low-boom redesign using the aeropropulsive Cart3D simulation and the calibrated mission analysis can be considered as an individual discipline feasible architecture [41] for MDO, where the coupling variables include two parameters for the calibrated lift method, design variables of the aircraft OML for low-boom shaping, engine thrust at SOC, and cruise weight at SOC. No effort is made to optimize the mission performance in this paper. Instead, the least intrusive approach is used to satisfy the consistency constraint between the aeropropulsive CFD simulation and the calibrated mission analysis by adjusting MTOGW to achieve the weight consistency at SOC (see Step 6 in Fig. 15). Further studies are required to understand whether there exists a better integration of low-boom optimization using aeropropulsive CFD simulation and mission performance optimization.

Steps 1 to 4 of the iteration method in Fig. 15 are already demonstrated in the previous two sections. Step 2 in Fig. 15 is only needed if the CFD engine generated in Sec. IV operates at a different thrust setting. The termination of the iteration method in Fig. 15 yields a low-boom concept with the CFD engines at SOC determined by the mission analysis calibrated using the aeropropulsive CFD simulation data.

For the aeropropulsive CFD simulation, the lift coefficient C_L is computed without using the pressure distribution on the non-lifting surfaces (or the internal surfaces) of the CFD engine (see Fig. 16). To make A_e due to lift consistent with the C_L calculation for the aeropropulsive CFD simulation, an interface code automatically redefines the pressure on all non-lifting surfaces of the engine to be zero (see Fig. 16) before using the surface pressure data for calculation of A_e due to lift. This ensures the correctness of the following equation {see eq. (7) in Ref. [42]}, which is the key mathematical foundation for the calibrated lift method in Ref. [5].

$$A_{e,\text{CFD}}(l_e) = \text{Lift } A_e \text{ value at } l_e = \frac{\beta}{\rho_\infty \cdot U_\infty^2} \cdot W_{\text{crs}} \quad (2)$$

The total lift from the modified surface pressure distribution is the aerodynamic lift that matches the cruise weight W_{crs} at SOC. With the modified pressure distribution, the calibrated lift method in Ref. [5] can be directly used for calibration of low-fidelity aerodynamic analyses using the aeropropulsive CFD simulation data. The calibrated lift method is implemented using a truncation parameter y_π (see Fig. 17) for the wing root section. Only the wing geometry from $y = y_\pi$ to the wing tip is used for low-fidelity aerodynamic analyses. The truncated wing is shifted so that the root airfoil is at $y = 0$. This truncated and shifted wing will be called the calibrated wing. The calibrated wing is used to generate the wing geometry inputs for low-fidelity aerodynamic analysis codes. The value of y_π will be determined by the low-fidelity aerodynamic analysis code LTSTAR [23] and the CFD analysis: the total wing lift from LTSTAR

applied to the calibrated wing equals the total CFD lift from the modified pressure distribution for the watertight geometry up to the end of the wing in the effective distance direction, which is labeled as $x_{e,tte}$ in Fig. 17 and determined by the blue Mach angle cut plane passing through the trailing edge of the wing tip airfoil. The tail lift is calibrated using a tail deflection angle adjustment parameter θ_Δ (see Fig. 17). This parameter determines the calibrated tail deflection angle ($\theta_{htail} - \theta_\Delta$) for low-fidelity aerodynamic analyses of any configuration with a tail deflection angle of θ_{htail} . The calibrated tail deflection angle makes the total tail lift from LTSTAR equal the total CFD lift from the modified pressure distribution after the blue Mach angle cut plane in Fig. 17, which includes the lift generated by the pylon and horizontal tail, as well as the interference lift from the nacelle and fuselage. This calibrated lift method using the modified pressure distribution allows the calibrated LTSTAR to generate the same wing lift and total lift as the aeropropulsive CFD simulation at SOC. See Ref. [5] for details about how to compute y_{rt} and θ_Δ from the CFD data.

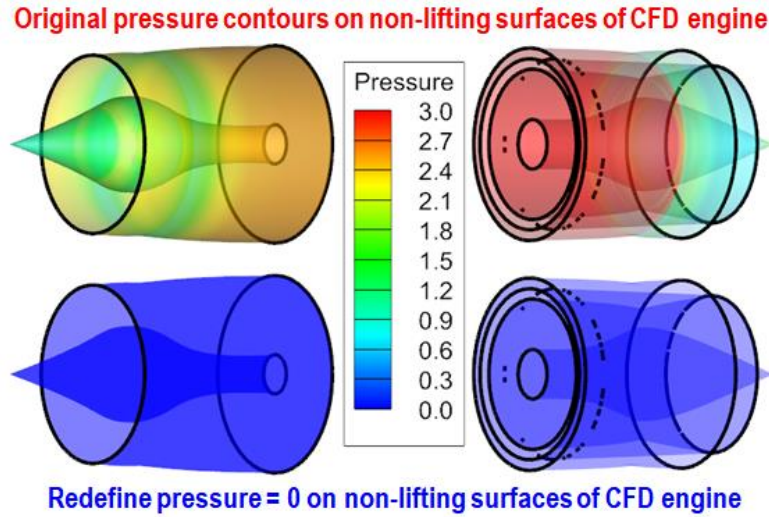


Fig. 16 Modification of pressure on non-lifting surfaces of CFD engine for calculation of A_e due to lift.

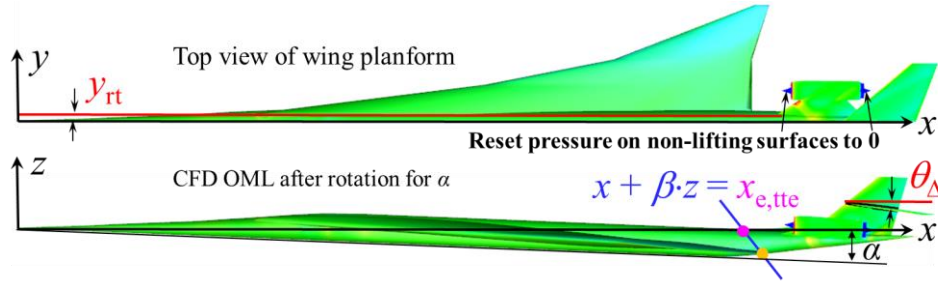


Fig. 17 Two parameters for the calibrated lift method using the modified pressure distribution.

With the modified pressure distribution data, the calibration equation {see eq. (3) in Ref. [5]} yields y_{rt} of 1.441 ft and θ_Δ of 3.568 deg. These two calibration parameters are slightly different from $y_{rt} = 1.270$ ft and $\theta_\Delta = 3.803$ deg for the Mach 1.7 40-PAX concept with the flow-through nacelles. For calculations of the wave and skin friction drags using the methods in Refs. [43,44], respectively, the engine is remodeled as a flow-through nacelle with its inlet capture area identical to the nacelle exit area. For MTOGW of 144,251 lb, the weight at SOC from the mission analysis calibrated using the aeropropulsive CFD simulation data is 133,811 lb for the redesigned powered concept, which is slightly higher than 133,594 lb for the flow-through concept. The start-of-cruise weight difference is mainly caused by the y_{rt} and θ_Δ differences, but differences in the pylon twist angle and nacelle shape could affect the wave and skin friction drags for the mission analysis.

To ensure that the low-boom redesign using the aeropropulsive CFD simulation is performed for the start-of-cruise condition of the calibrated mission analysis, MTOGW is used as the design variable in Step 6 of Fig. 15 to make the start-of-cruise weight match what was used for the low-boom redesign using the aeropropulsive CFD simulation. After

reducing MTOGW to 143,990 lb, the weight at SOC matches that of the flow-through concept. The required engine thrust of 8594 lb from the calibrated mission analysis differs from the CFD engine thrust (see Table 2) by 13.4 lb, a difference about 0.2% of the required thrust. So, the redesigned powered concept with MTOGW of 143,990 lb achieves the consistency between the FLOPS mission analysis, NPSS engine analysis, and low-boom redesign using the aeropropulsive Cart3D simulation.

The iteration method in Fig. 15 terminates in one iteration with 1% as the error tolerance for difference between the CFD engine thrust and the required engine thrust at SOC from the mission analysis. Note that, if more drastic OML changes are required to obtain a redesigned powered concept, then the performance of the redesigned powered concept might be significantly different from the original flow-through concept, which could result in a more significant change of the required thrust at SOC. Then another optimization of the CFD engine might be needed. Even in this case, the change of the CFD engine would be minimal because only the inflow BC and throat areas of the two nozzles are used for the thrust adjustment (see Step 2 in Fig. 15). The iteration method in Fig. 15 is expected to terminate after a few iterations with a relative error tolerance of 1% for the CFD engine thrust and the required engine thrust at SOC.

For this low-boom redesign study using the aeropropulsive Cart3D simulation, the flow-through and redesigned powered concepts are nearly identical in terms of mission performance. The MTOGW difference of 261 lb is negligible. The overland and overwater ranges of the redesigned powered concept are 3537 and 3955 nm, respectively, which differ from those of the flow-through concept (see Table 1) by less than 1%. The low-fidelity lift-to-drag ratios at SOC using the calibrated aerodynamic analyses are 7.73 and 7.77 for the flow-through and redesigned powered concepts, respectively. The relative difference of the lift-to-drag ratios is about 0.5%. The redesigned powered concept with MTOGW of 143,990 lb is a feasible solution of Eq. (1). So, Eq. (1) using the aeropropulsive Cart3D simulation for sonic boom analysis can be solved using the BCO method in Ref. [5], followed by the iterative method in Fig. 15, to obtain a supersonic transport that satisfies both the low-boom and mission performance constraints.

VII. Conclusions

A CFD-based low-boom concept with flow-through nacelles is redesigned using the aeropropulsive Cart3D [19] simulation. The NPSS [7] engine for the mission analysis is approximated using a CFD engine at the start of overland cruise (SOC). Nine engine dimension and performance parameters are selected as the coupling variables between the NPSS engine analysis and aeropropulsive Cart3D simulation for engine plume simulation. Their values for the CFD engine are very close to those of the NPSS engine with a maximum relative difference of 1.7% for the coupling consistency. For the low-boom redesign study using an axisymmetric engine in this paper, replacing the flow-through nacelle with a CFD engine has a marginal effect on the low-boom characteristics of the original low-boom concept with the flow-through nacelles. Only a change of the pylon twist angle from 0 to 1 deg is required to restore a close match between the $A_{e,r}$ of the redesigned powered concept and the $A_{e,r}$ target of 69.9 PLdB for the flow-through concept.

An iteration method is introduced to couple the FLOPS [25] mission analysis, NPSS engine analysis, and low-boom redesign using the aeropropulsive Cart3D simulation. For the low-boom redesign study in this paper, only one iteration is required to achieve the following coupling consistency at SOC for the redesigned powered concept: 1) the calibrated low-fidelity aerodynamic analysis generates the same wing lift and total lift as the aeropropulsive CFD simulation, 2) the CFD engine thrust matches the required engine thrust determined by the mission analysis using the calibrated aerodynamic analyses, 3) the CFD engine and NPSS engine have the identical nozzle BCs and approximately the same mass flow and thrust, and 4) the redesigned powered concept is an acceptable inverse design for an $A_{e,r}$ target of 69.9 PLdB. The numerical example in this paper demonstrates that there exists a supersonic transport satisfying both the low-boom and mission performance requirements, even if an aeropropulsive CFD simulation is required for sonic boom analysis. Further studies are needed to understand whether the CFD engine approximation method is applicable to an NPSS engine that is not axisymmetric.

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References

- [1] Morgenstern, J., Norstrud, N., Stelmack, M., and Jha, P., "Advanced Concept Studies for Supersonic Commercial Transports Entering Service in 2030-2035 (N+3)," AIAA Paper 2010-5114, June 2010. doi:[10.2514/6.2010-5114](https://doi.org/10.2514/6.2010-5114)

- [2] Stevens, S., "Perceived Level of Noise by Mark VII and Decibels (E)," *Journal of the Acoustical Society of America*, Vol. 51, No. 2B, 1972, pp. 575–601. doi:[10.1121/1.1912880](https://doi.org/10.1121/1.1912880)
- [3] Chapman, K., "The X Factor—QueSST Exclusive," *Air International*, Sep. 2022, pp. 28–39.
- [4] Park, M., and Carter, M., "Low-Boom Demonstrator Near-Field Summary for the Third AIAA Sonic Boom Prediction Workshop," *Journal of Aircraft*, Vol. 59, No. 3, 2022, pp. 563–577. doi:[10.2514/1.C036323](https://doi.org/10.2514/1.C036323)
- [5] Li, W., and Geiselhart, K., "Multi-objective, Multidisciplinary Optimization of Low-Boom Supersonic Transports Using Multifidelity Models," *Journal of Aircraft*, Vol. 59, No. 5, 2022, pp. 1137–1151. doi:[10.2514/1.C036656](https://doi.org/10.2514/1.C036656).
- [6] Huff, D., Henderson, B., Berton, J., and Seidel, J., "Perceived Noise Analysis for Offset Jets Applied to Commercial Supersonic Aircraft," AIAA Paper 2016-1635, Jan. 2016. doi:[10.2514/6.2016-1635](https://doi.org/10.2514/6.2016-1635)
- [7] *Numerical Propulsion System Simulation (NPSS), Version 2.8*, Southwest Research Institute, URL:<https://www.swri.org/consortia/numerical-propulsion-system-simulation-npss> [retrieved 2 June 2022].
- [8] Park, M., and Nemec, M., "Nearfield Summary and Statistical Analysis of the Second AIAA Sonic Boom Prediction Workshop," *Journal of Aircraft*, Vol. 56, No. 3, 2019, pp. 851–875. doi:[10.2514/6.2017-3256](https://doi.org/10.2514/6.2017-3256)
- [9] Rodriguez, D., "Propulsion/Airframe Integration and Optimization on a Supersonic Business Jet," AIAA Paper 2007-1048, Jan. 2007. doi:[10.2514/6.2007-1048](https://doi.org/10.2514/6.2007-1048)
- [10] Li, W., Campbell, R., Geiselhart, K., Shields, E., Nayani, S., and Shenoy, R., "Integration of Engine, Plume, and CFD Analyses in Conceptual Design of Low-Boom Supersonic Aircraft," AIAA 2009-1171, Jan. 2009. doi:[10.2514/6.2009-1171](https://doi.org/10.2514/6.2009-1171)
- [11] Berens, T., "Aerodynamic Propulsion Integration for Supersonic Business Jets," AIAA Paper 2010-6591, July 2010. doi:[10.2514/6.2010-6591](https://doi.org/10.2514/6.2010-6591)
- [12] Wintzer, M., Ordaz, I., and Fenbert, J., "Under-Track CFD-Based Shape Optimization for a Low-Boom Demonstrator Concept," AIAA Paper 2015-2260, June 2015. doi:[10.2514/6.2015-2260](https://doi.org/10.2514/6.2015-2260)
- [13] Heath, C., Seidel, J., and Rallabhandi, S., "Viscous Aerodynamic Shape Optimization with Installed Propulsion Effects," AIAA Paper 2017-3046, June 2017. doi:[10.2514/6.2017-3046](https://doi.org/10.2514/6.2017-3046)
- [14] Wintzer, M., Castner, R., and Geiselhart, K., "Airframe-Nozzle-Plume Interactions in the Context of Low Sonic Boom Design," AIAA Paper 2015-1045, Jan. 2015. doi:[10.2514/6.2015-1045](https://doi.org/10.2514/6.2015-1045)
- [15] Connolly, J., Kopasakis, G., Chwalowski, P., Sanetrik, M., Carlson, J., Silva, W., and McNamara, J., "Towards an Aero-Propulso-Servo-Elasticity Analysis of a Commercial Supersonic Transport," AIAA Paper 2016-1320, Jan. 2016. doi:[10.2514/6.2016-1320](https://doi.org/10.2514/6.2016-1320)
- [16] Heath, C., Slater, J., and Rallabhandi, S., "Inlet Trade Study for a Low-Boom Aircraft Demonstrator," *Journal of Aircraft*, Vol. 54, No. 4, 2017, pp. 1283–1293. doi:[10.2514/1.C034036](https://doi.org/10.2514/1.C034036)
- [17] Imrak, R., Karaselvi, E., Tutkun, B., and Nikbay, M., "Exploration of Optimal Propulsion System Airframe Integration Design Concepts for a Low Boom Supersonic Aircraft," AIAA Paper 2021-2469, Jan. 2021. doi:[10.2514/6.2021-2469](https://doi.org/10.2514/6.2021-2469)
- [18] Yildirim, A., Gray, J., Mader, C., and Martins, J., "Boundary Layer Ingestion Benefit for the STARC-ABL Concept," *Journal of Aircraft*, Vol. 59, No. 4, 2022, pp. 896–911. doi:[10.2514/1.C036103](https://doi.org/10.2514/1.C036103)
- [19] *Cart3D, Version 1.5*, NASA, URL:<https://www.nas.nasa.gov/software/cart3d.html> [retrieved 2 June 2022].
- [20] Li, W., and Rallabhandi, S., "Inverse Design of Low-Boom Supersonic Concepts Using Reversed Equivalent-Area Targets," *Journal of Aircraft*, Vol. 51, No. 1, 2014, pp. 29–36. doi:[10.2514/1.C031551](https://doi.org/10.2514/1.C031551)
- [21] Ordaz, I., and Li, W., "Integration of Off-Track Sonic Boom Analysis in Conceptual Design of Supersonic Aircraft," *Journal of Aircraft*, Vol. 51, No. 1, 2014, pp. 23–28. doi:[10.2514/1.C031511](https://doi.org/10.2514/1.C031511)
- [22] Li, W., and Geiselhart, K., "Multidisciplinary Design Optimization of Low-Boom Supersonic Aircraft with Mission Constraints," *AIAA Journal*, Vol. 59, No. 1, 2021, pp. 165–179. doi:[10.2514/1.J059237](https://doi.org/10.2514/1.J059237)
- [23] Carlson, H., and Mack, R., "Estimation of Wing Nonlinear Aerodynamic Characteristics at Supersonic Speeds," NASA TP-1718, November 1980.
- [24] Wolz, R., "A Summary of Recent Supersonic Vehicle Studies at Gulfstream Aerospace," AIAA Paper 2003-558, Jan. 2003. doi:[10.2514/6.2003-558](https://doi.org/10.2514/6.2003-558)
- [25] McCullers, L., *FLOPS User's Guide*, NASA Langley Research Center, Hampton, Virginia, 2011 (available with public distribution of software).
- [26] *Code of Federal Regulations*, National Archives, URL:<https://www.ecfr.gov/current/title-14/chapter-I/subchapter-F/part-91/subpart-F/section-91.533> [retrieved 2 June 2022]
- [27] *U.S. Standard Atmosphere*, 1976, U.S. Government Printing Office, Washington, D.C., 1976. URL:https://www.ngdc.noaa.gov/stp/space-weather/online-publications/miscellaneous/us-standard-atmosphere-1976/us-standard-atmosphere_st76-1562_noaa.pdf [retrieved 26 July 2022].
- [28] *Method for Calculation of the Absorption of Sound by the Atmosphere, Annex C*, American National Standards Inst., Standard S1.26-1995, New York, 1995.

- [29] Rallabhandi, S., and Loubeau, A., “Summary of Propagation Cases of the Third AIAA Sonic Boom Prediction Workshop,” *Journal of Aircraft*, Vol. 59, No. 3, 2022, pp. 578–594. doi:[10.2514/1.C036327](https://doi.org/10.2514/1.C036327)
- [30] *OpenVSP, Version 3.16.1*, NASA, URL:<http://openvsp.org/> [retrieved 2 June 2022].
- [31] Slater, J., “SUPIN: A Computational Tool for Supersonic Inlet Design,” AIAA Paper 2016-0530, Jan. 2016. doi:[10.2514/6.2016-0530](https://doi.org/10.2514/6.2016-0530)
- [32] Chima, R., “Analysis of Buzz in a Supersonic Inlet,” NASA TM-2012-217612, May 2012.
- [33] Tong, M., and Naylor, B., “An Object-Oriented Computer Code for Aircraft Engine Weight Estimation,” NASA TM-2009-215656, Dec. 2009.
- [34] *ModelCenter, Version 12.0*, Phoenix Integration Inc., URL:<http://www.phoenix-int.com> [retrieved 26 Feb. 2023].
- [35] Blumenthal, B., Elmilgui, A., Geiselhart, K., Campbell, K., Maughmer, M., and Schmitz, S., “Computational Investigation of a Boundary-Layer-Ingestion Propulsion System,” *Journal of Aircraft*, Vol. 55, No. 3, 2018, pp. 1141–1153. doi:[10.2514/1.C034454](https://doi.org/10.2514/1.C034454)
- [36] Palumbo, O., Palmer, D., Wall, T., Gulati, S., and Coder, J., “Propulsion/Airframe Integration Study for Ultra High Bypass Ratio Turbofan and a Slotted, Natural-Laminar-Flow Wing,” AIAA Paper 2022-2481, Jan. 2022. doi:[10.2514/6.2022-2481](https://doi.org/10.2514/6.2022-2481)
- [37] Li, W., and Geiselhart, K., “Integration of Low-Fidelity MDO and CFD-Based Redesign of Low-Boom Supersonic Transports,” *AIAA Journal*, Vol. 59, No. 10, 2021, pp. 3923–3936. doi:[10.2514/1.J060368](https://doi.org/10.2514/1.J060368)
- [38] Ordaz, I., Geiselhart, K., and Fenbert, J., “Conceptual Design of Low-Boom Aircraft with Flight Trim Requirement,” *Journal of Aircraft*, Vol. 52, No. 3, 2015, pp. 932–939. doi:[10.2514/1.C033160](https://doi.org/10.2514/1.C033160)
- [39] Li, W., “Feasibility of Supersonic Aircraft Concepts for Low-Boom and Flight Trim Constraints,” AIAA Paper 2015-2581, June 2015. doi:[10.2514/6.2015-2581](https://doi.org/10.2514/6.2015-2581)
- [40] Li, W., “Equivalent Area Targets for Inverse Design Optimization with Changing Low-Boom Cruise Conditions,” *AIAA Journal*, Vol. 61, No. 3, 2023, pp. 1260–1269. doi:[10.2514/1.J062324](https://doi.org/10.2514/1.J062324)
- [41] Martins, J., and Lambe, A., “Multidisciplinary Design Optimization: a Survey of Architectures,” *AIAA Journal*, Vol. 51, No. 9, 2013, pp. 2049–2075. doi:[10.2514/1.J051895](https://doi.org/10.2514/1.J051895)
- [42] Seebass, R., and George, A., “Sonic Boom Minimization,” *Journal of the Acoustical Society of America*, Vol. 51, No. 2C, 1972, pp. 686–694. doi:[10.1121/1.1912902](https://doi.org/10.1121/1.1912902)
- [43] Harris, R., Jr., “An Analysis and Correlation of Aircraft Wave Drag,” NASA TM X-947, March 1964.
- [44] Sommer, S., and Short, B., “Free-Flight Measurements of Turbulent-Boundary-Layer Skin Friction in the Presence of Severe Aerodynamic Heating at Mach Numbers from 2.8 to 7.0,” NACA TN-3391, 1955.