

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

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A low-boom supersonic transport was designed for a cruise Mach of 1.7 and 40 passengers. This low-boom aircraft, referred to as the Mach 1.7 40-PAX concept, was generated using computational fluid dynamics (CFD) based sonic boom analysis 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) and modeled as a flow-through nacelle for CFD analysis. To understand how the engine plume affects the undertrack ground signature, the Mach 1.7 40-PAX concept is redesigned using an 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 configuration with the CFD engines is optimized to approximately restore the low-boom characteristics of the Mach 1.7 40-PAX concept. Finally, the CFD simulation data for the optimized 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 low-boom supersonic transports.

Nomenclature

A_e	= any equivalent area, including $A_{e,r}$ and $A_{e,CFD}$, ft ²
$A_{e,r}$	= reversed equivalent area defined by using reverse propagation of off-body pressure, ft ²
$A_{e,CFD}$	= equivalent area defined using Mach angle cut method and computational fluid dynamics, ft ²
C_L	= lift coefficient
dp/p	= nondimensional overpressure $(p-p_\infty)/p_\infty$
l_e	= effective length of a configuration, which is the largest effective distance where Mach angle cut plane intersects the configuration, 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
SOC	= start of overland cruise
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_{rt}	= 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 $\sqrt{M^2 - 1}$
θ_{tail}	= deflection angle of an all-moving horizontal tail at SOC, deg

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θ_{Δ} = calibration parameter for θ_{htail} , deg
 ρ_{∞} = ambient density at SOC, lb/ft³

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], 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 multiobjective multidisciplinary optimization (MDO) method called the block coordinate optimization (BCO) method. The BCO method dissects a multiobjective 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 [4]. 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. [4] 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 was designed using the Numerical Propulsion System Simulation (NPSS) [5]. NPSS was used to generate the engine weight and performance data for mission analysis. For full-vehicle CFD analyses, this NPSS engine 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 by a powered engine, the Mach 1.7 40-PAX concept is redesigned using an aeropropulsive CFD simulation for sonic boom analysis in this paper. To enable the aeropropulsive CFD simulation, a design process is introduced to construct a CFD engine mimicking the NPSS engine of the Mach 1.7 40-PAX concept. After installing the CFD engine on the Mach 1.7 40-PAX concept, a low-boom concept using the aeropropulsive CFD simulation for sonic boom analysis is generated with the pylon twist angle and tail deflection angle as design variables. Moreover, an iteration method is used to ensure that the optimized low-boom concept with the CFD engines is designed for SOC determined by the mission analysis using low-fidelity aerodynamic analyses calibrated by the aeropropulsive CFD simulation of the optimized low-boom concept. This low-boom redesign study demonstrates the possibility for a consistent coupling of the mission analysis, NPSS engine analysis, and low-boom redesign using the aeropropulsive CFD simulation. It also illustrates how the propulsion-airframe integration could be implemented for conceptual design of low-boom supersonic transports.

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 Section III. In Section 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 [6] is used for all CFD analyses in this paper. An automated meshing process [7] 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.

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.

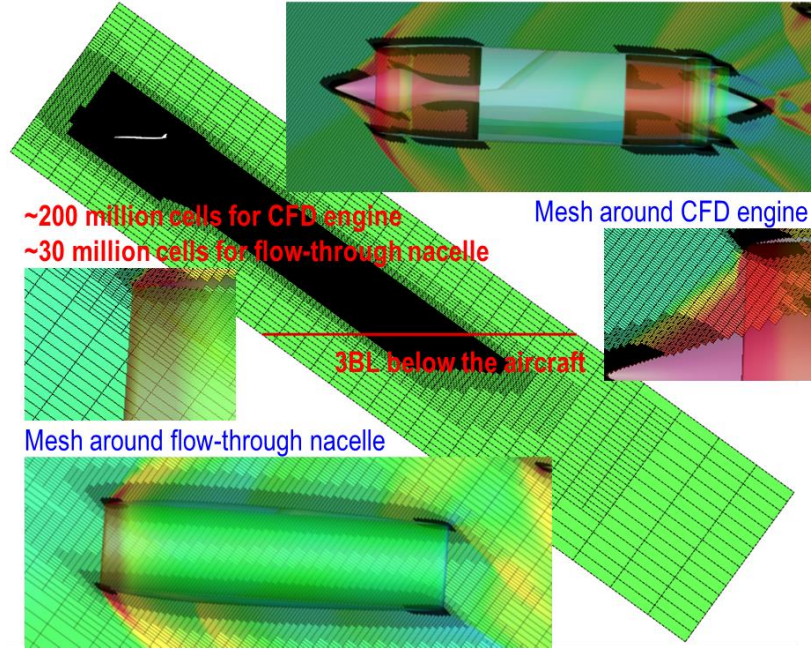


Fig. 1 Cart3D meshes for off-body pressure calculation with CFD engine or flow-through nacelle.

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. Note that the thrust term used in this paper refers to the net thrust per engine.

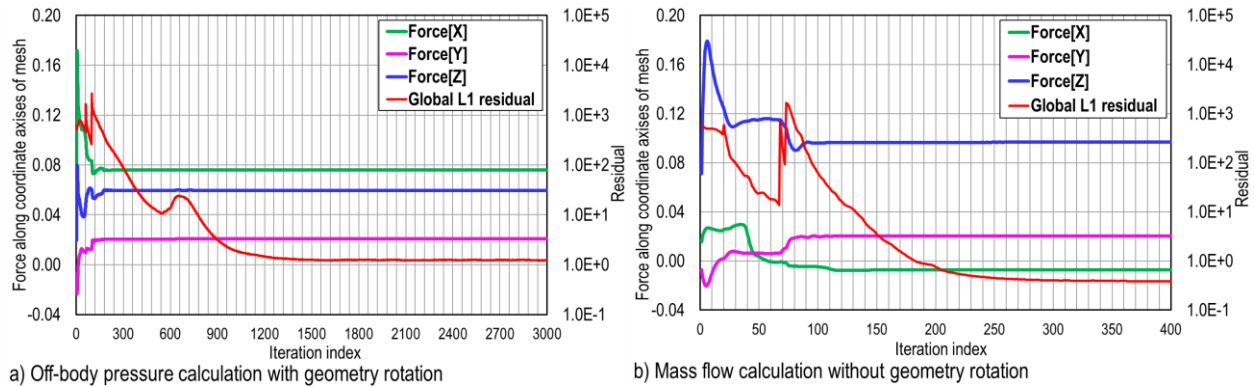


Fig. 2 Typical convergence histories for aeropropulsive Cart3D simulation.

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

The Mach 1.7 40-PAX concept is the low-boom supersonic transport in Ref. [4] with a more detailed cabin layout (see Figs. 3 and 4). The seat pitch is reduced from 48 inches for the low-boom concept in Ref. [4] to 46 inches due to the required spaces for two lavatories, which were not considered in Ref. [4]. 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. [8]. 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) [9] for mission analysis. The ranges from the mission analysis are marginally longer than those in Ref. [4] 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 [10], while two attendants were used for mission analysis in Ref. [4]. See Ref. [4] for a detailed description of the analysis methods used in the FLOPS mission analysis.

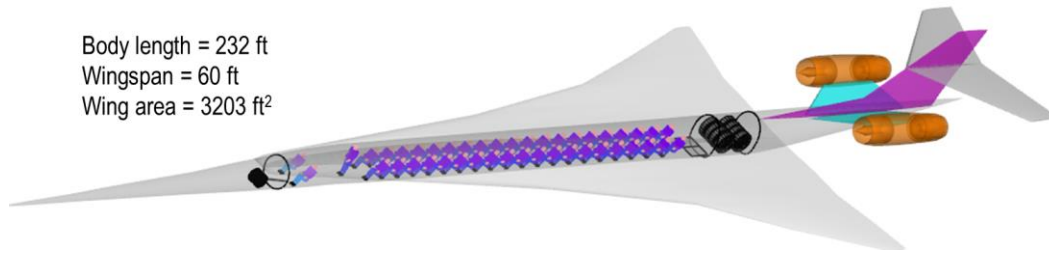


Fig. 3 Mach 1.7 40-PAX concept.

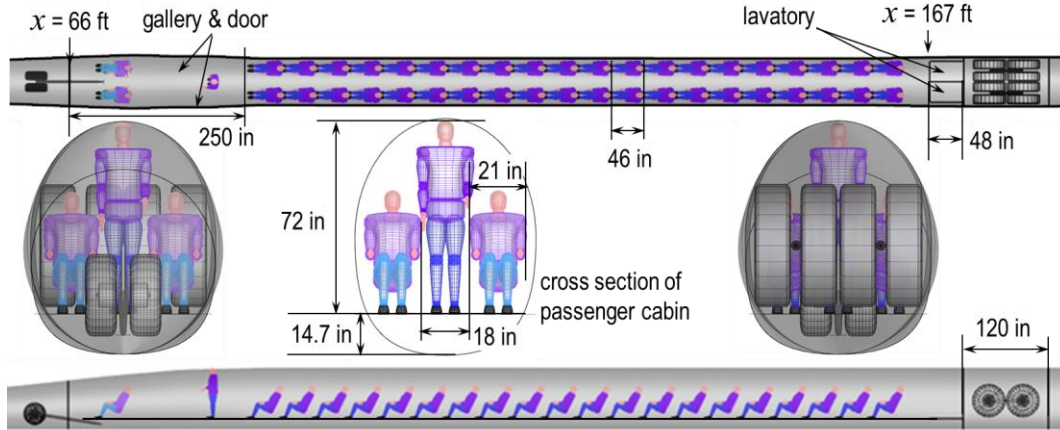


Fig. 4 Detailed cabin layout of Mach 1.7 40-PAX concept.

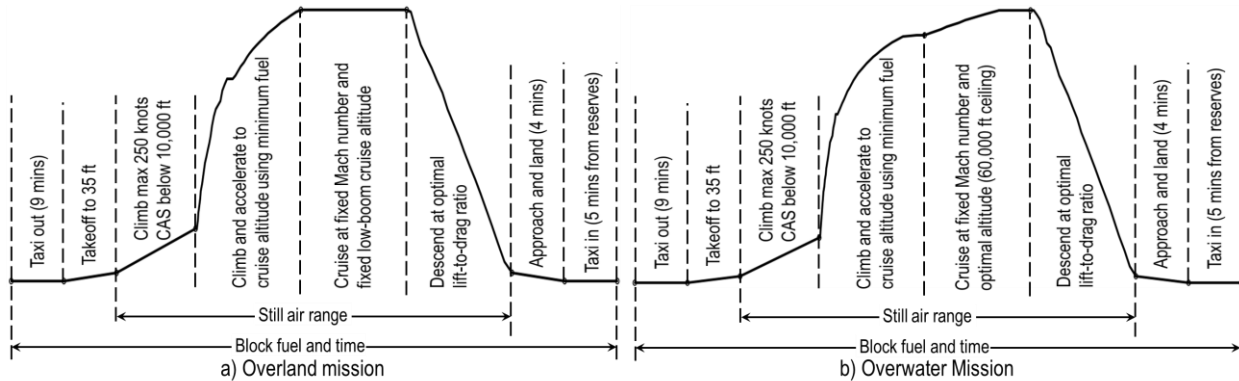


Fig. 5 Overland and overwater mission profiles.

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

The Mach 1.7 40-PAX concept is an acceptable CFD-based low-boom inverse design for a given reversed equivalent area ($A_{e,r}$) [11] 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 [11]. 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 [12]. See sec. II.F in Ref. [4] for the involved formulas. The humidity profile for the standard atmosphere is based on ANSI S1.26 [13]. 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 [14,15], 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. [4], even though the same OpenVSP [16] 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.

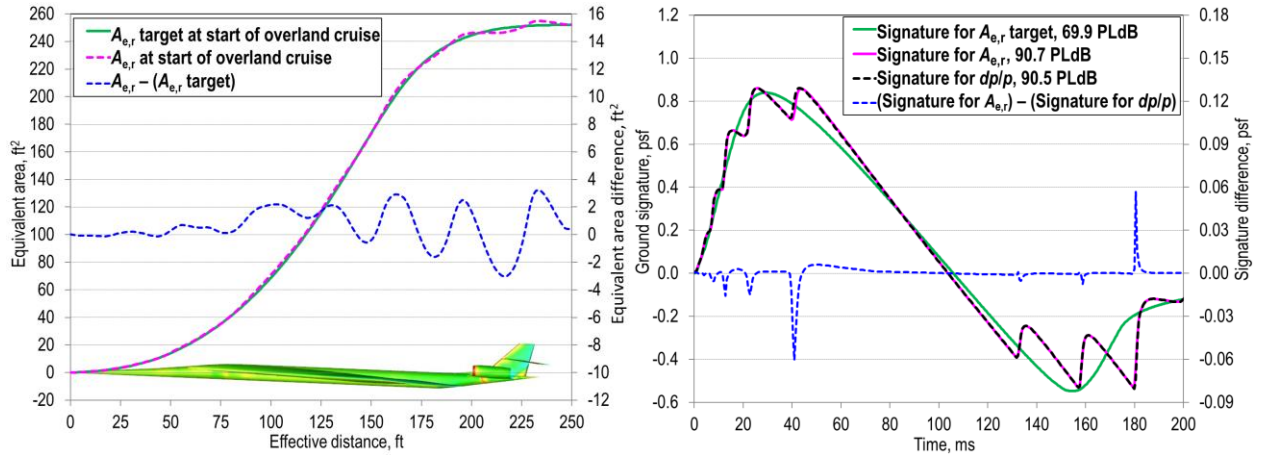


Fig. 6 Equivalent areas and undertrack ground signatures at SOC.

IV. Approximation of NPSS Engine by CFD Engine

This section documents how to construct a CFD engine (see Fig. 7) as an approximation of an NPSS engine for the aeropropulsive Cart3D simulation, which is a novel approach for the propulsion-airframe integration. The CFD engine in Fig. 7 follows a standard approach of using inflow and outflow boundary conditions (BCs) in CFD analysis to study aerodynamic interactions between the propulsion system and airframe. 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. [14,17]), optimization of inlet and nozzle shapes of an engine on a supersonic business jet [18], plume shapes for various nozzles of an engine on a low-boom concept [19], evaluations of aerodynamic drag and intake performance of a supersonic business jet using different engines [20], adjoint-based low-boom shaping of a supersonic demonstrator with a single engine [21,22], effects of different engines on ground signatures of two low-boom configurations with and without nozzle shock shielding [23], static aeroelastic analysis of a supersonic configuration with engines [24], and impacts of different engines on ground signatures of a low-boom configuration [25,26].

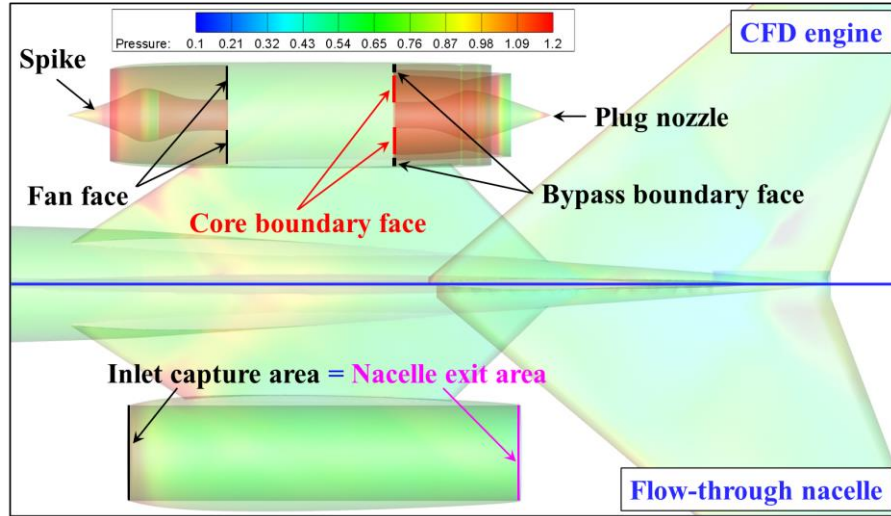


Fig. 7 CFD engine and flow-through nacelle for the Mach 1.7 40-PAX concept.

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. [23,25], 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. [24] 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. [22] for design of a low-boom supersonic demonstrator. In Ref. [22], the inlet performance map from the aeropropulsive CFD simulation was used by the NPSS engine to determine the 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. 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 implemented in Ref. [27] to study the potential benefits of boundary layer ingestion for subsonic aircraft. 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.

The propulsion-airframe integration in this paper is for conceptual design of low-boom supersonic aircraft. The coupling scope includes the FLOPS 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 FLOPS mission analysis data. Then, the relevant dimension and performance parameters of the NPSS engine 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 NPSS engine thrust at SOC. Next, a low-boom configuration with the CFD engines is generated using the aeropropulsive Cart3D simulation for sonic boom analysis. Finally, the FLOPS mission analysis is repeated for the low-boom concept with the CFD engines using the calibrated low-fidelity aerodynamic analyses based on the Cart3D simulation data for the same concept. An iterative method is used to achieve the coupling consistency for the disciplinary analyses. This section only covers the approximation of the NPSS engine and the remaining integration steps will be discussed in the next two sections.

To be consistent for disciplinary coupling between the aeropropulsive Cart3D simulation and NPSS engine analysis, the CFD engine should be a good approximation of the NPSS engine at SOC and have the following properties: 1) there is no significant spillage at the inlet lip, 2) the mass inflow matches the mass outflow, 3) the CFD engine thrust matches the NPSS engine thrust at SOC, and 4) the key dimension and performance parameters of the NPSS engine are retained by the CFD engine. The last property is to ensure that the CFD engine generates a plume consistent with the NPSS engine performance at SOC.

The NPSS engine has a variable area nozzle for throat and exit areas to achieve optimal performance with the required thrust at each operating condition, while the CFD engine has a fixed shape for SOC. The process for approximation of an NPSS engine at SOC by a CFD engine can be briefly summarized as follows.

- 1) Construct a parametric OpenVSP geometry model for a CFD engine.
- 2) Extract the NPSS engine BCs and dimension parameters for the required thrust at SOC determined by the FLOPS mission analysis.
- 3) Use the supersonic inlet design tool SUPIN [28] and the relevant NPSS engine parameters to design the inlet (including the spike) and nacelle OML up to the fan face.
- 4) Construct an initial engine geometry with a compatible static pressure ratio as the inflow BC at the fan face for the aeropropulsive Cart3D simulation using the NPSS engine dimension parameters as guidance.
- 5) Use a Mach contour plot around the engine from the Cart3D solution as guidance to change the inlet lip diameter, location, and spike shape for reduction of spillage.
- 6) Minimize the difference between the mass inflow and outflow and match the CFD engine thrust with the NPSS engine thrust using the inflow BC and fourteen cross section diameters of the OpenVSP engine as the design variables.
- 7) If the required thrust or cruise altitude is changed, update the BCs at the nozzle boundary faces with the NPSS nozzle BCs for the new operating condition. Then, minimize the difference between the mass inflow and outflow and match the CFD engine thrust with the NPSS engine thrust using the inflow BC and throat areas of the two nozzles as the design variables.

A notional NPSS engine geometry (see Fig. 8) is constructed using the NPSS engine 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 NPSS engine at SOC. But some shape parameters are determined empirically due to a lack of the geometry details for the NPSS engine. This notional NPSS engine was used 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).

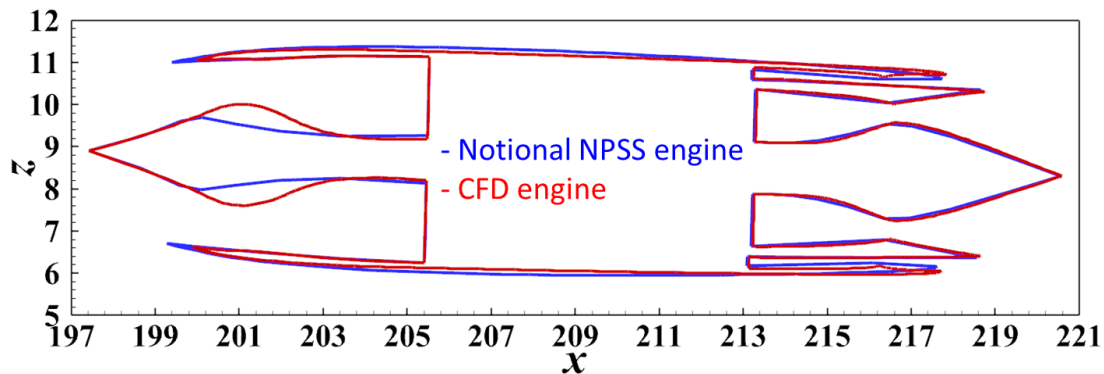


Fig. 8 Notional NPSS engine to define the flow-through nacelle and its CFD engine approximation.

For the aeropropulsive Cart3D simulation, the inlet (including the spike) and nacelle OML up to the fan face are redesigned using SUPIN. SUPIN is capable of generating an inlet shape for CFD analysis [28]. The key input parameters for SUPIN include 1) the cruise Mach of 1.7 and altitude of 52,240 ft as the freestream flight condition,

and 2) the fan-face dimension parameters and the mass inflow at the fan face for SOC from NPSS. See sec. II.C of Ref. [28] for details.

Then, the aeropropulsive Cart3D simulation is used to guide the CFD engine shape modifications. Three sets of BCs are used for the aeropropulsive Cart3D simulation: 1) a static pressure ratio of 4.06 for inflow at the fan face, 2) a total pressure ratio of 3.04 and a total temperature ratio of 2.69 for outflow at the core boundary face, and 3) a total pressure ratio of 1.53 and a total temperature ratio of 1.18 for outflow at the bypass boundary face. The specified ratios are from the NPSS engine data at SOC for the Mach 1.7 40-PAX concept.

Next, an initial engine is constructed using the NPSS engine dimension parameters as guidance. Due to the fidelity gap between NPSS and CFD analyses, the NPSS static pressure ratio as the inflow BC at the fan face might be incompatible with the aeropropulsive Cart3D simulation, which will be shown later for the CFD engine in Fig. 8. Empirical adjustments of the inflow BC are required to achieve the desired engine flow characteristics (see Fig. 9). Here the desired engine flow characteristics are determined conceptually: 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. Once the aeropropulsive Cart3D simulation generates a solution with the desired engine flow characteristics, the inlet lip diameter, location, and spike shape are empirically adjusted to reduce the spillage at the inlet lip, based on the visual inspection of a Mach contour plot such as Fig. 9.

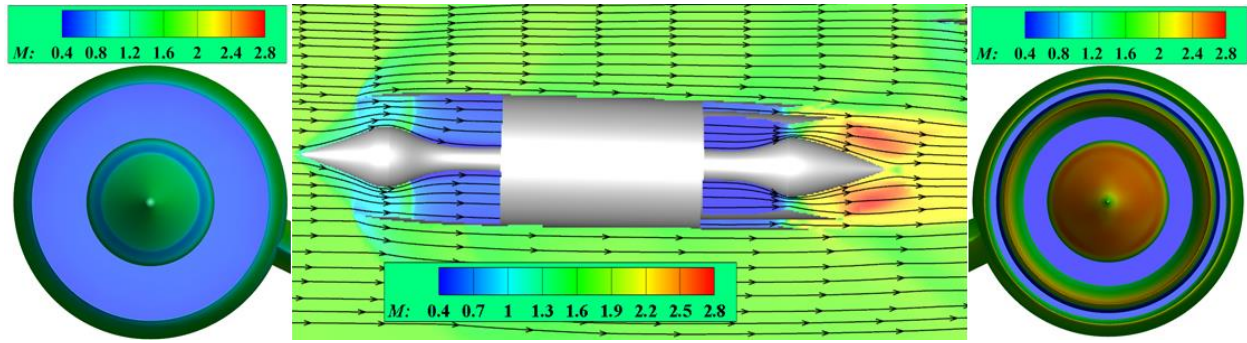


Fig. 9 Mach contours and streamlines around the CFD engine on the Mach 1.7 40-PAX concept.

Finally, the inflow BC at the fan face and fourteen cross section diameters of the OpenVSP engine are used as the design variables for engine optimization. The engine optimization aims to achieve the mass flow balance for the engine while matching the CFD engine thrust with the NPSS engine thrust. The objective function is the relative error for the mass flow balance, which is defined as $|(mass\ inflow) - (mass\ outflow)| / (mass\ outflow)$. The thrust match is enforced with an equality constraint: CFD engine thrust = NPSS engine thrust of 8,640 lb for the Mach 1.7 40-PAX concept at SOC. The engine optimization is terminated once the relative errors for the thrust constraint and mass flow balance are less than 1%. For the engine optimization, the design variables related to the dimension parameters of the NPSS engine are constrained with lower and upper bounds so that the optimized engine is reasonably close to the NPSS engine in terms of approximation errors of dimension parameters.

Figure 8 compares the shapes of the notional NPSS engine 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. 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. The total pressure recovery for the CFD engine is about 90%. Table 2 compares some key dimension and performance parameters of the NPSS engine at SOC and the CFD engine. The dimension and performance parameters of the CFD engine are very close to those of the NPSS engine, with a maximum relative difference of 1.7%, except the five parameters marked with red color. The noticeable modifications of 4.9 to 17.1% of the five NPSS parameters in Table 2 are used for the CFD engine to minimize the spillage at the inlet lip, achieve the mass flow balance, and match the NPSS engine thrust.

To illustrate the necessity of changing the NPSS inflow BC for the CFD engine, the aeropropulsive Cart3D simulation is reperformed using the NPSS static pressure ratio of 4.06 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 10 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 and a significant spillage at the inlet lip. The computed mass inflow of 25.7 lb/sec at the fan face is about 10% of the computed mass outflow of 246.7 lb/sec at the nozzle boundary faces. Mathematically, it means that the mass inflow as a function of the static pressure ratio is not always meaningfully defined, which makes the engine optimization difficult to solve if the range of the static pressure ratio is not properly constrained. Note that some CFD

solvers [29,30] 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 and remove the mass flow relative error as the objective for the engine optimization, which will make the resulting engine optimization problem much easier to solve. However, the current version of Cart3D [6] does not have the option of using the mass inflow as the BC at the fan face.

Table 2 Parameters for the NPSS engine and the corresponding CFD engine

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

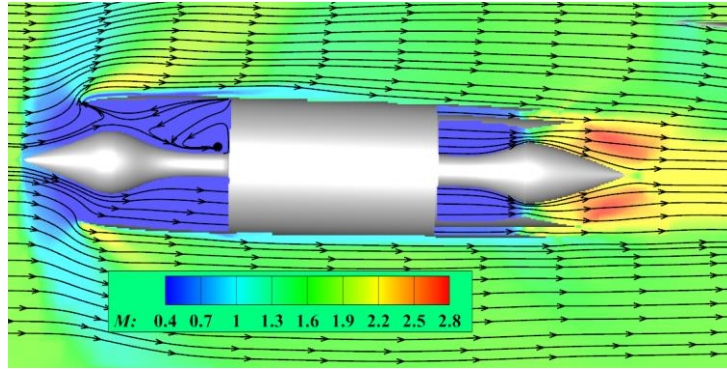


Fig. 10 Mach contours and streamlines around the CFD engine with a non-compatible inflow BC.

Changes to the required thrust and cruise altitude can be modeled as different operating conditions for the engine. For such a different engine operating condition, the corresponding NPSS BCs at the nozzle boundary faces are used for the aeropropulsive Cart3D simulation. The engine optimization is reperformed with the inflow BC and throat areas of the two nozzles as the design variables. So, the constructed CFD engine can be used to simulate the NPSS engine at any operating condition with variations of three parameters.

For a more consistent integration of an NPSS engine in an aeropropulsive CFD simulation, it is desirable to develop an NPSS engine model that can be realized by a CFD engine without significant changes of the key dimension and performance parameters. Moreover, the current process for approximation of an NPSS engine at a specified operating condition by a CFD engine is highly empirical. Further studies are required for development of a more rigorous approximation of an NPSS engine by a CFD engine.

V. Low-Boom Redesign Using Aeropropulsive CFD Simulation

A comprehensive low-boom shaping study using an aeropropulsive CFD simulation was conducted for a low-boom flight demonstrator of one seat, one engine, a body length of 108 ft, and a wingspan of 30 ft [21]. The low-boom shaping was performed for 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 by 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 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 computational cost of obtaining a supersonic configuration with undertrack sonic boom ground noise level around 76 PLdB is very high. There is no guarantee that such a configuration could be obtained for the required lift coefficient even with flow-through nacelles [21]. 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. 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 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 to attain the final low-boom shape (see the introduction of Ref. [4]).

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.

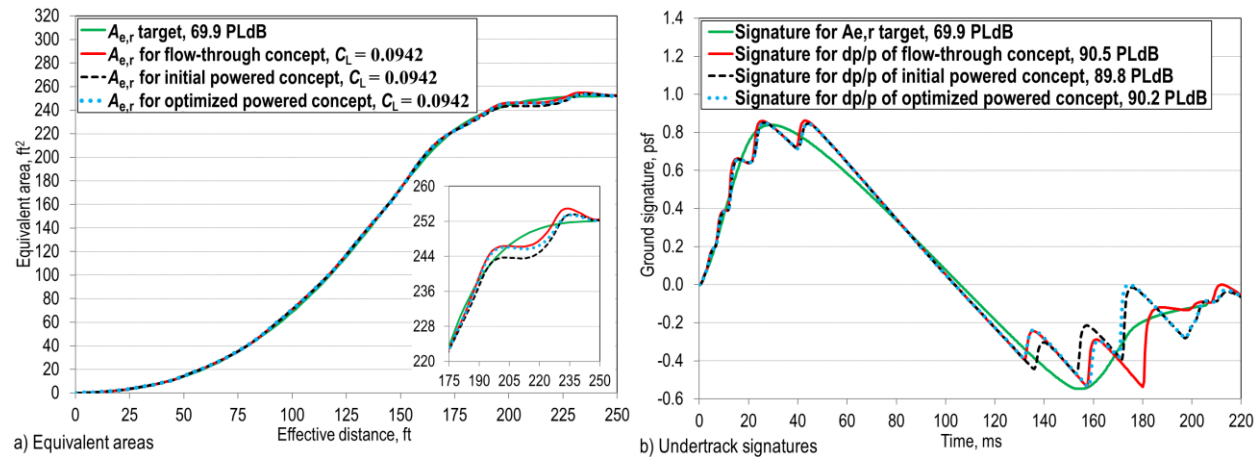


Fig. 11 Equivalent areas and ground signatures for flow-through and powered concepts.

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 4.57 deg will be called the initial powered concept. Then, 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. After a parametric study using the aeropropulsive Cart3D simulation, an optimized 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 optimized powered concept matches the $A_{e,r}$ target closer than that of the initial powered concept (see Fig. 11a). The optimized 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. 11b). The flow-through and optimized 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. 11b and 12), but its effects on the $A_{e,r}$ shape and the PLdB value of the undertrack ground signature are negligible (see Fig. 11). Both the initial and optimized powered concepts can be considered as acceptable low-boom inverse design solutions for the $A_{e,r}$ target of 69.9 PLdB.

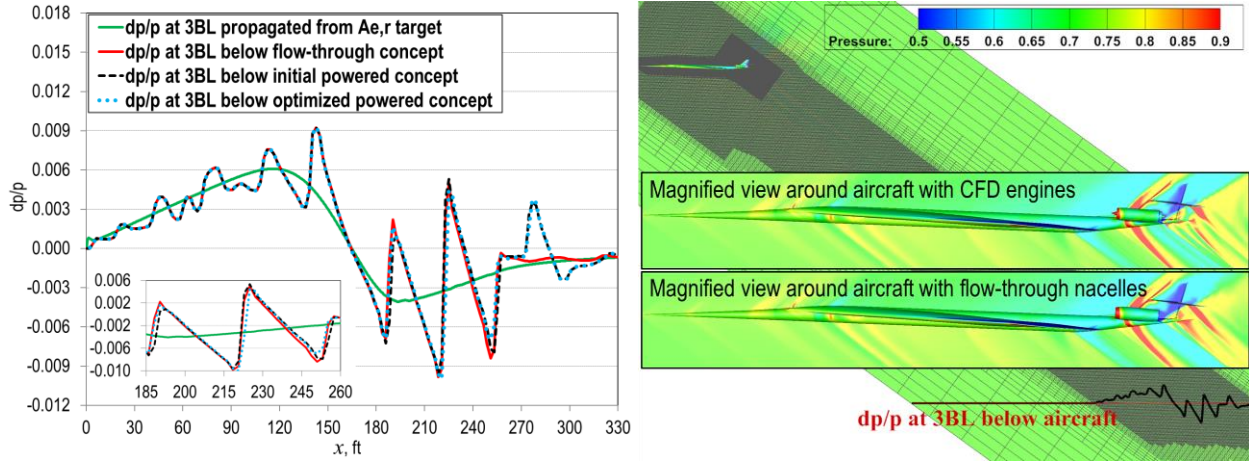


Fig. 12 Off-body pressures for flow-through and powered concepts.

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 [4] 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 optimized powered concept. This section shows how to achieve a coupling consistency between the FLOPS mission analysis and sonic boom analysis using the aeropropulsive CFD 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. 13.

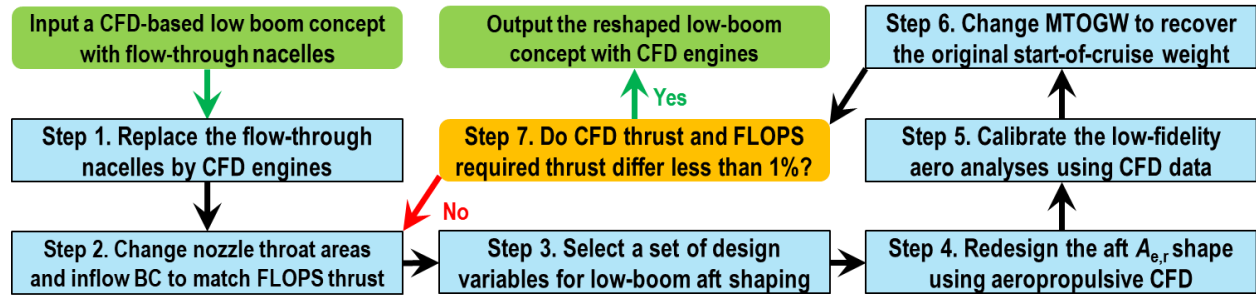


Fig. 13 Integration of mission analysis with low-boom redesign using aeropropulsive CFD simulation.

Steps 1 to 4 of the iteration method in Fig. 13 are already demonstrated in the previous two sections. Step 2 in Fig. 13 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. 13 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. 14). 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. 14) 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. [31]), which is the key mathematical foundation for the calibrated lift method in Ref. [4].

$$A_{e,CFD}(l_e) = \text{Lift } A_e \text{ value at } l_e = \frac{\beta}{\rho_\infty \cdot U_\infty^2} \cdot W_{crs} \quad (1)$$

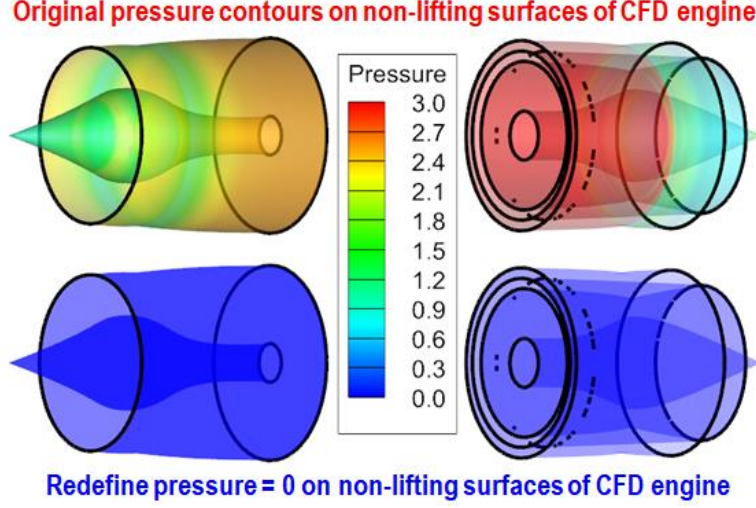


Fig. 14 Modification of pressure on non-lifting surfaces of CFD engine for calculation of A_e due to lift.

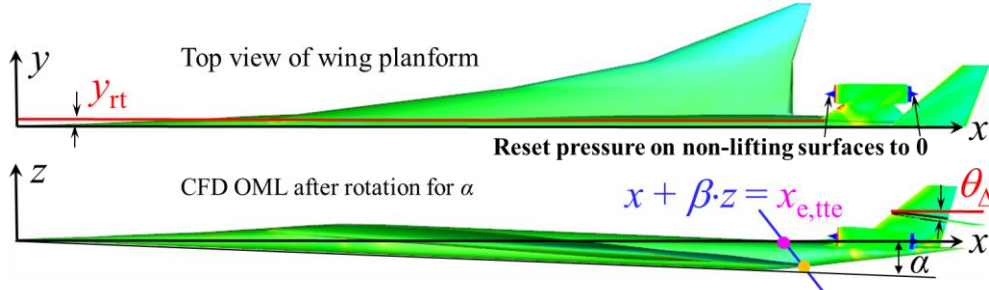


Fig. 15 Two parameters for the calibrated lift method using the modified pressure distribution.

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. [4] 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_{rt} (see Fig. 15) for the wing root section. Only the wing geometry from $y = y_{rt}$ 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_{rt} will be determined by the low-fidelity aerodynamic analysis code LTSTAR [32] 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. 15 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. 15). 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. 15, 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. [4] for details about how to compute y_{π} and θ_{Δ} from the CFD data.

With the modified pressure distribution data, the calibration equation (see eq. (3) in Ref. [4]) yields y_{π} of 1.441 ft and θ_{Δ} of 3.568 deg. These two calibration parameters are slightly different from $y_{\pi} = 1.270$ 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. [33,34], 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 optimized 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_{π} 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. 13 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 optimized 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. 13 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 an optimized powered concept, then the performance of the optimized 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 minimum because only the inflow BC and throat areas of the two nozzles are used for the thrust adjustment (see Step 2 in Fig. 13). The iteration method in Fig. 13 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 optimized 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 optimized powered concept are 3537 and 3955 nm, respectively, which differ from those of the flow-through concept (see Table 1) with less than 1% relative difference. 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 optimized powered concepts, respectively. The relative difference of the lift-to-drag ratios is about 0.5%.

VII. Conclusions

A CFD-based low-boom concept with flow-through nacelles is redesigned using the aeropropulsive Cart3D [6] simulation. The NPSS [5] engine for the mission analysis is approximated using a CFD engine at the start of overland cruise (SOC). Nine of the fourteen dimension and performance parameters of the CFD engine are very close to those of the NPSS engine with a maximum relative difference of 1.7%. The noticeable modifications of the remaining five parameters are used for the CFD engine to minimize the spillage at the inlet lip, achieve the mass flow balance, and match the NPSS engine thrust. 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 optimized 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 [9] 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 optimized 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 optimized powered concept is an acceptable inverse design for an $A_{e,r}$ target of 69.9 PLdB.

The low-boom redesign study using the aeropropulsive CFD simulation aims to solve the same multiobjective low-boom MDO problem [eq. (4)] in Ref. [4], except that CFD engines instead of flow-through nacelles are used for CFD analysis. The iteration method in Fig. 13 solves this MDO problem for CFD engines under the assumption that the multiobjective low-boom MDO problem for flow-through nacelles is already solved using the BCO method in Ref. [4]. So, the iteration method in Fig. 13 is an extension to the BCO method for solving the same MDO problem using the aeropropulsive CFD simulation. The mission analysis and NPSS engine analysis use a multidisciplinary feasible (MDF) architecture [35] for MDO with the sea-level static thrust of the NPSS engine as the coupling variable [4]. The aeropropulsive CFD simulation and NPSS engine analysis use an approximation of an MDF architecture with fourteen coupling variables, due to some inconsistencies in five engine dimension and performance parameters. These inconsistencies or consistency constraint violations are the consequences of the fidelity gap between the NPSS engine and the CFD engine, which can only be eliminated by an improvement of the analysis fidelity of the NPSS engine. This fidelity gap could lead to some uncertainties in the MTOGW and range predictions, but its effect on the off-body pressure is considered to be minimum, because of the close match of the performance parameters at the nozzle boundary faces and the thrusts of the two engines. The cyclic dependency between the low-boom redesign using the aeropropulsive CFD simulation and the calibrated mission analysis can be considered as an individual discipline feasible architecture [35] for MDO, where the coupling variables are the two calibration parameters y_{it} and θ_A for the calibrated lift method, design variables for low-boom shaping, required engine thrust, 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. Further studies are required to understand whether the optimized powered concept can be improved by a better integration of low-boom redesign using the aeropropulsive CFD simulation and mission performance optimization.

Acknowledgments

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