Project 47 Clean-sheet Supersonic Aircraft Engine Design and Performance

Massachusetts Institute of Technology

Project Lead Investigator

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- P.I.: Prof. Steven R. H. Barrett
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 052, 059, 074, 076, 090, 106, 110, and 115 (NCE to September 30, 2024)
- Period of Performance: March 29, 2019 to September 30, 2024 (with the exception of funding and cost-share information, this report covers the period from October 1, 2022 to September 30, 2023)
- Tasks:
    1. Evaluate the effects of fan diameter and unconventional architectures on the environmental impacts of clean-sheet engines

Project Funding Level

$1,650,000 FAA funding and $1,650,000 matching funds. Sources of match are approximately $340,000 from MIT, plus third-party in-kind contributions of $177,000 from Byogy Renewables, Inc.; $982,000 from NuFuels, LLC; and $151,000 from Savion Aerospace Corporation.

Investigation Team

Prof. Steven Barrett, (P.I.), Task 1
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Project Overview

Engines for supersonic aircraft, compared with those for subsonic aircraft, present unique challenges in terms of fuel consumption, noise, and emissions impacts, because of their unique operating conditions. The propulsion systems currently proposed by the industry are derivative engines (Figure 1) designed around the unmodified core (high-pressure compressor, combustor, and high-pressure turbine) of existing subsonic engines, with modifications to the low-pressure spool (fan and low-pressure turbine).

This project is aimed at evaluating the design space of "clean-sheet" engines designed specifically for use on civil supersonic aircraft, and to determine the resulting environmental performance of such engines. Unlike previous commercial supersonic engines, which were adapted from military aircraft, or planned propulsion systems derived from current commercial engines, a clean-sheet engine takes advantage of recent advances in propulsion system technology to substantially improve performance and reduce emissions and noise footprints. This project will quantify these benefits for a range of engine designs relevant to currently proposed civil supersonic aircraft. Conventional clean-sheet engines have been examined by the Project 47 team. To further characterize the clean-sheet design space, more unconventional engine architectures, namely hybrid-electric systems, are investigated. Specifically, we aim to assess the relative performance of hybrid-electric clean-sheet and conventional clean-sheet engines.

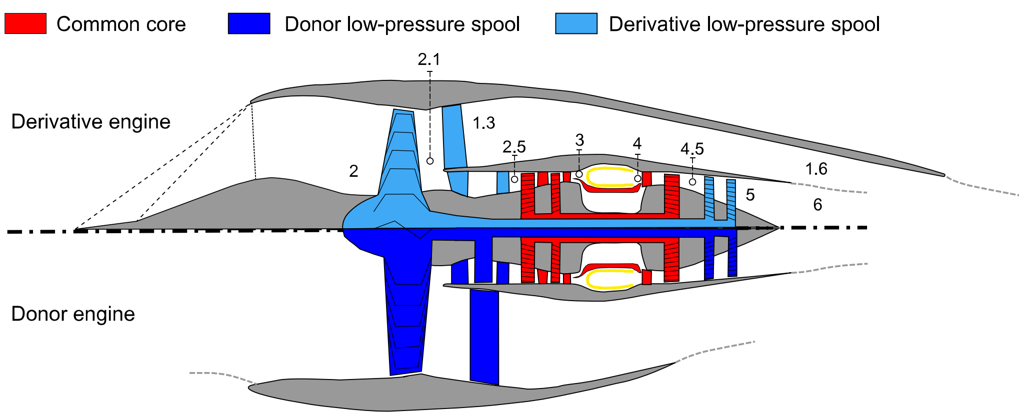

Figure 1. Engine architecture schematic. The lower half shows the subsonic donor engine. The high-pressure spool (red) core is used in the derivative engine (top half) along with modifications to the inlet, fan, and nozzle, as shown in the top half.

Task 1 – Evaluate the Effects of Fan Diameter and Unconventional Architectures on the Environmental Impacts of Clean-Sheet Engines

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Objective

The objective of this task is to quantify the effects of fan diameter constraints and use of unconventional engine architectures on the emissions of clean-sheet engines. In particular, we examine the combined impact of the following cases:

- Effect of fan diameter on supersonic drag sources, and subsequent impacts on thrust requirements and engine performance
- Use of hybrid-electric systems powered primarily with conventional fuel alongside a battery-based supplement used during landing and takeoff (LTO) flight

The work presented is done for the airframe and mission of the Supersonic Transport Concept Aircraft (STCA) developed by NASA (Berton et al., 2020).

Research Approach

Numerical Propulsion System Simulation (NPSS) software (Claus et al., 1991) was chosen for analysis of engine performance and emissions. Because it is an industry-standard tool, it facilitates future collaboration with the broad user base. The clean-sheet engine cycle deck from Prashanth et al. (2023) is used to obtain a baseline design.

Supersonic drag sources

Supersonic drag forces on an engine fall primarily into three categories: bypass drag, spillage drag, and wave drag. Bypass and spillage drag represent losses due to off-design operation of a supersonic inlet. In this work, engine inlets are assumed to be operated on-design or to contain variable-geometry components to maintain well-matched operation across the mission. Therefore, we assume that the contributions of spillage and bypass drag are negligible. The effects of such systems (weight, complexity, etc.) are not considered here.

The Fraenkel model for external cowl drag on open-nosed bodies of revolution (as presented by Seddon and Goldsmith (1999)) is used to model the remaining supersonic drag source, wave drag. The aspect ratio of the inlet cross-section (radius/length) is taken to be constant and equal to the value for the existing STCA engine. Fan diameter is used as a proxy for maximum inlet radius and is allowed to vary. A conical profile is conservatively used to minimize drag.

Although the exact value of the wave drag due to the engine inlet cowls on the baseline aircraft is unknown, it can be estimated with the above model. Consequently, the difference in wave drag can be estimated for a clean-sheet engine with a specified fan diameter relative to the baseline design. This difference is then used alongside steady flight assumptions to obtain the difference in thrust requirement relative to the baseline mission presented in Berton et al. (2020).

Previous hybrid-electric assessments

Before implementing a full hybrid-electric NPSS engine model, we first qualitatively assess the potential benefits of hybrid electrification. We assume an architecture wherein electric systems are used only during the LTO phase of flight, when the greatest demand is placed on the engine. Consequently, the gas turbine component of the engine can be sized more closely to cruise requirements. Similar analyses in subsonic systems (Kang et al., 2022; Lammen & Vankan, 2020; Lents et al., 2016; Seitz et al., 2018) suggest specific fuel consumption benefits on the order of 5%, alongside minor improvements to nitrogen oxide (NO_x) emissions. These benefits are hypothesized to manifest through three primary mechanisms:

- Lower peak gas turbine corrected fan speed requirement: This aspect could allow the gas turbine to operate closer to the design condition (100% corrected speed) during cruise, improving component efficiency.
- Lower peak engine turbine-entry-temperature (TET): If the maximum TET point occurs during LTO, electric systems could be used to reduce the TET required by the gas turbine, thereby potentially improving NO_x emissions and propulsive efficiency.
- Lower thrust requirements at pinch points: Electric systems could be used to reduce the thrust requirements of the gas turbine at the pinch points of the mission, thereby allowing the engine to be sized more closely to cruise thrust requirements.

The final mechanism, thrust requirement, was implemented indirectly to maintain the known mission profile. The time in the mission at which a given constraint is placed was varied, and the altitude, Mach number, and thrust requirement could then be calculated at that new time. As an example, the thrust pinch point occurs at 27 kft at a Mach number of 0.85. In a hybrid-electric engine, the gas turbine would not be able to produce sufficient thrust at that point alone and would require assistance by the electric systems. To model this scenario while maintaining the STCA mission profile, the engine is sized for thrust at a slightly later (positive time deviation) or slightly earlier (negative time deviation) mission point. An engine sized for thrust at either of these points will not produce sufficient thrust at the actual thrust pinch point but may be sized more optimally for cruise. This procedure of varying the time at which a thrust constraint is applied is repeated for other key points in the mission.

To test these mechanisms, NPSS is used to examine the sensitivity of emissions metrics to the corrected fan speed, turbine inlet temperature, and thrust requirement (with time as a proxy) at several points in the STCA LTO profile. These points are the thrust pinch point (27 kft., Mach 0.85), the thermal pinch point (42 kft., Mach 1.4), and the aerodynamic design point (ADP; 41 kft., Mach 1.4). Emissions are then evaluated at the beginning of cruise point (44 kft., Mach 1.4) as an estimate of overall cruise emissions.

Major Accomplishments

Supersonic drag implementation

The wave drag was first estimated for several supersonic regime Mach numbers for the original STCA engine design. The fan diameter (D_f) was then allowed to vary. The percentage deviation in drag area ($C_d A$) is shown in Figure 2 as a function of Mach number. The drag area of an engine cowl monotonically increases with a local sensitivity of $\partial C_d A / \partial D_f = 3.5$. The drag area relative to the baseline STCA was found to have minimal variation due to the Mach number. At a fixed fan diameter, the change in drag area was between 1.6% at -10% fan diameter and 3.3% at $+10\%$ fan diameter. Notably, the effect of Mach number grows with increasing fan diameter, thus indicating that this effect would need to be accounted for at high fan diameters.

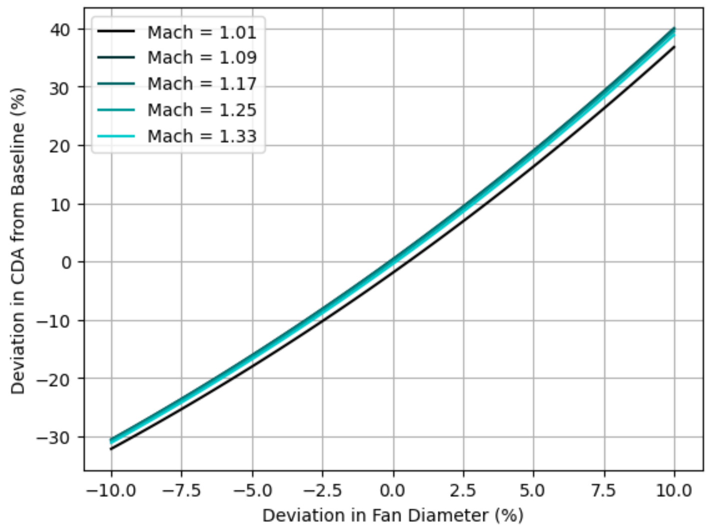

Figure 2. Effect of fan diameter variation on engine external cowl drag area (CDA), as a function of Mach number.

Sensitivities

The supersonic drag model described above was implemented into the NPSS clean-sheet cycle deck, and sensitivities of specific air range (SAR), thrust specific fuel consumption (SFC), and fan diameter were calculated due to variation in TET, corrected fan speed, and thrust (with time as a proxy). The resulting sensitivities are generally non-linear (Figure 3). Variations in emissions metrics and fan diameter due to turbine inlet temperature have negligible dependence on the point at which the temperature was prescribed, thus suggesting strong correlations between temperature changes at one point with resulting changes at the other two points. We see improved SAR and SFC for increasing turbine inlet temperature, to maxima on the order of 0.5%. SFC was minimized with a corrected fan speed deviation of -5% for all three points of interest. While SAR exhibits a maximum, the value of that maximum is decreased, because of the resultant increase in fan diameter and thus drag.

The emissions and fan diameter sensitivities due to sizing time variation are not smooth, because variations in time equate to variations in altitude, Mach number, and thrust, in accordance with the prescribed LTO mission profile. As such, when an inflection point of the mission (e.g., end of climb) is reached, the behavior of the mission parameters with respect to time changes suddenly. From the time sensitivities, we see SAR and SFC benefits resulting from a positive deviation of time at the thrust pinch point. This finding indicates that sizing the engine thrust to a later point in the mission and producing insufficient thrust at the actual pinch point do improve cruise emissions.

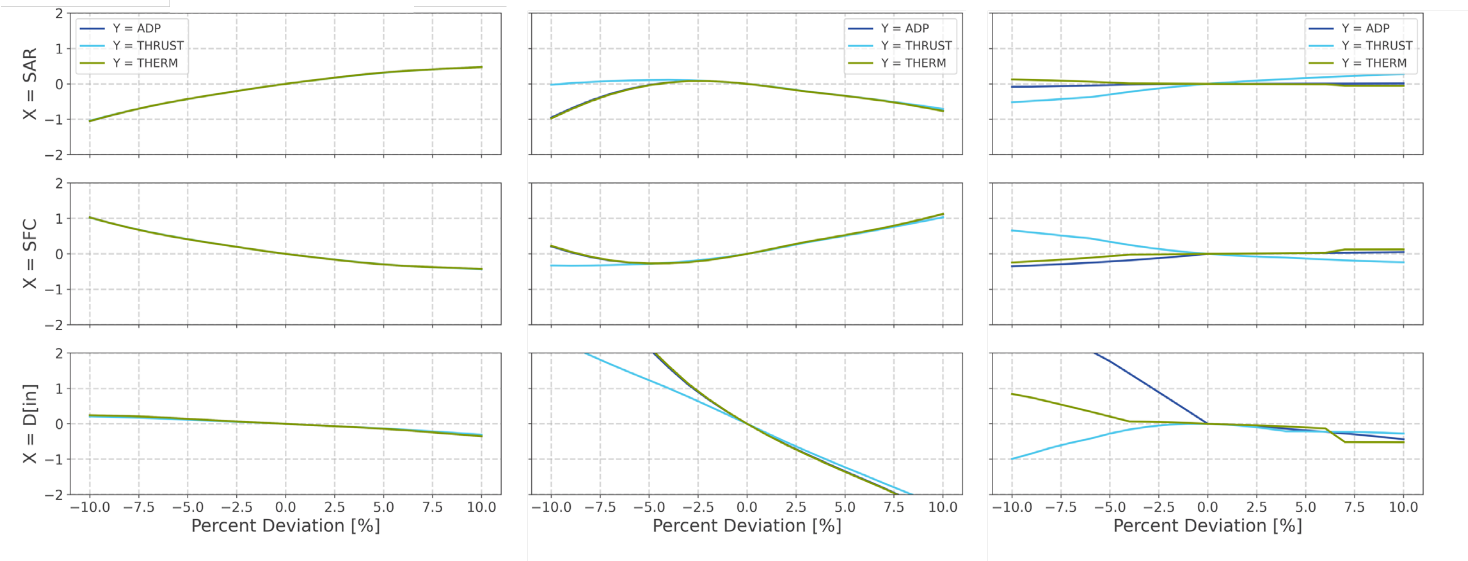

Figure 3. Sensitivity of metric *X* at the beginning of cruise to turbine inlet temperature (left), corrected fan speed (middle), and time (right) at point *Y*.

Publications

None

Outreach Efforts

Results were presented to the FAA Project Manager during regular teleconferences.

Awards

None

Student Involvement

This work was performed primarily by graduate research assistant Wyatt Giroux, working under the supervision of Dr. Prakash Prashanth, Dr. Jayant Sabnis, Dr. Raymond Speth, and Dr. Choon Tan.

Plans for Next Period

In the next period, we will create a dedicated hybrid electric NPSS engine model including the effects on thrust requirement due to battery weight, nacelle weight, and nacelle drag. This model, alongside the sensitivities above, will be used to determine optimal hybrid-electric engine designs for several fan diameters and electric system sizes. These results will then be compared with the results obtained by Prashanth et al. (2023) for conventional clean-sheet designs, to determine the effects of hybrid electrification on SST emissions.

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