
# NASA'S EFFICIENT QUIET INTEGRATED PROPULSORS (EQUIP) TECHNICAL CHALLENGE

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## Abstract

Advances in aircraft propulsor technology - ducted and unducted - are key elements to developing a sustainable aviation future. Increasing propulsive efficiency comes with significant challenges. The long-term trend in aircraft engine design has been towards higher bypass ratios to increase efficiency and decrease noise. Current designs are pushing against limits on engine size; the engine must fit under the wing and overcome the nacelle weight, aerodynamic drag, and airframe integration penalties associated with an ultra-high bypass ratio. The next-generation ducted engines will have shorter inlets and smaller rotor-stator spacing to minimize nacelle area. This increases the potential for non-uniform flow at the fan face and less area for acoustic liners. Unducted engines eliminate the nacelle penalty while presenting challenges to noise and operability in distorted flow environments. The overall diameter in both cases raises questions about engine-airframe integration to maximize efficiency gains and minimize installation penalties. The National Aeronautics and Space Administration (NASA) Advanced Air Vehicles Program (AAVP) approved the Efficient Quiet Integrated Propulsor (EQuIP) Technical Challenge (TC) under the Advanced Air Transport Technology (AATT) Project to work on next-generation propulsor technologies in collaboration with NASA's government and industry partners in the Sustainable Flight National Partnership. The EQuIP TC leverages NASA resources with Federal Aviation Administration (FAA) and industry investments under the FAA's Continuous Lower Energy Emissions and Noise (CLEEN) program to address technical challenges *on the propulsor* subject to the flow field imposed by the engine-airframe-flight environment. The EQuIP TC complements NASA Aeronautics Research Mission Directorate's (ARMD) existing investments in sustainable aviation for the next-generation of commercial aircraft and contributes to meeting the noise and efficiency goals set by the Sustainable Flight National Partnership and U.S. Aviation Climate Action Plan. This paper introduces the EQuIP TC, describes key parts of its development, and presents the background research used to scope its impact.

**Keywords:** keywords list Propulsion, Integration, Public-Private Partnerships (not more than 5)

## 1. General Introduction

The U.N. World Commission on Environment and Development defined "sustainable development" as "meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs"[1]. Technology that contributes to sustainable development must be environmentally friendly, socially acceptable, and economically viable to drive adoption into the market and support the future economy. The U.S. Sustainable Flight National Partnership (SFNP) calls for National Aeronautics and Space Administration (NASA), the Federal Aviation Administration (FAA), and other U.S. government agencies to work with academia and the aviation industry towards a sustainable aviation future starting with an opportunity to advance a new single-aisle commercial aircraft in the 2030's.

The SFNP seeks a step-change reduction in fuel burn and noise for the next generation of aircraft in the 2030's. This is a key milestone to meeting the larger challenge of net-zero aviation emissions with aircraft noise reductions presented in the U.S. Aviation Climate Action Plan[1]. The technologies

[1]https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf, downloaded December 2023.

required to meet these aggressive fuel burn, emissions and noise goals must also enable growth in aviation to meet the society's expanding need for transportation of people and goods at affordable prices.

The NASA Aeronautics Research Mission Directorate (ARMD) is leading the transformation of aviation in four key technical areas: Ultra-Efficient Airliners, Future Airspace and Safety, High-Speed Commercial Flight, and Advanced Air Mobility. In the near-term, subsonic commercial airliners account for the vast majority of flight miles and are the focus of the SFNP goals for the 2030's. Under NASA's Aeronautics Strategic Implementation Plan[2], Strategic Thrust 3, targets Ultra-Efficient Subsonic Transports to "realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy". These goals are assigned to the Advanced Air Vehicles Program (AAVP) where the Hybrid Thermally Efficient Core (HyTEC) Demonstrator, Hi-Rate Composite Aircraft Manufacturing (HiCAM) Demonstrator, and Advanced Air Transport Technology (AATT) Project's Electrified Aircraft Propulsion (EAP) and Transonic Truss-Braced Wing (TTBW) Technical Challenges (TC) explore, advance, and enable new engine and airframe technologies (Figure 1). These projects and technical challenges, colloquially known as the "Fab 4", started in 2020/2021 achieve Technology Readiness Level (TRL)[3] 6 by 2028 in support of a 2030's aircraft (Figure 2).

Advanced propulsor technology is complementary to the other NASA key technologies; an efficient propulsor can be combined with a small-hybrid or electrified core on a TTBW airframe to significantly increase overall aircraft energy efficiency. The AATT Project saw an opportunity in 2022 to advance state-of-the-art propulsor technology in collaboration with the FAA and industry. AAVP subsequently gave AATT approval to plan and propose an integrated propulsor-airframe TC using the existing budget forecast and leveraging these external collaborations. The Efficient Quiet Integrated Propulsor (EQuIP) Technical Challenge (TC) was developed by the AATT team and approved by AAVP in March 2023.

The EQuIP TC leverages NASA's unique capabilities and FAA and industry investments under the FAA's Continuous Lower Energy Emissions and Noise (CLEEN)[4] program to advance propulsor technology for a new product in the 2030's. The EQuIP formulation team recognized that any new propulsor technology will likely seek to increase engine bypass ratio and, therefore, introduce significant engine-airframe integration challenges. These challenges exist on two fronts: the effect of the engine exhaust on the wing/airframe and the effect of the flow-field induced by the airframe on the propulsor. These challenges are exacerbated by the ultra-short nacelle or unducted propulsors necessary to increase engine bypass ratio beyond today's state of the art. *The EQuIP TC focuses on propulsor efficiency, noise, and operability in a relevant flow field that includes wing/airframe effects*. While NASA recognizes the need to address the effect of the propulsor on the wing/airframe, the team focused on the propulsor to maximize the available NASA resources by augmenting propulsor-focused FAA and industry efforts already underway at that time.

## 2. Introducing the EQuIP TC

The EQuIP TC was planned to leverage investments from the FAA CLEEN program and industry collaborations that complement NASA's expertise and unique capabilities. The TC plan includes execution of tests, analysis of data, model development, noise reduction technology design, and building a new capability to predict propulsor icing. Achieving all of these goals requires testing state of the art propulsor designs in a relevant environment. Public-private partnerships facilitate these tests of industry developed propulsors in NASA's unique experimental facilities to enable a high impact TC and are critical to meeting the United States' long-term sustainable aviation goals. The EQuIP TC contributions towards the Nation's goals — from NASA's point of view — are captured

[2]https://www.nasa.gov/wp-content/uploads/2021/04/sip-2023-final-508.pdf, downloaded December 2023.

[3]https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels, downloaded December 2023.

[4]The FAA CLEEN program is a public-private partnership that seeks to develop and demonstrate certifiable aircraft technology to: reduce aircraft fuel burn; reduce aircraft emissions; reduce aircraft noise; and advance sustainable aviation fuels. More information can be found at:
https://www.faa.gov/about/office_org/headquarters_offices/apl/eee/technology_saf_operations/cleen


Figure 1 – The NASA AAVP's key demonstrators and technical challenges advancing sustainable aviation technology for the next-generation commercial aircraft (colloquially called the "Fab 4").

in the TC objectives statement:

> Assess, model, and predict the ability for next-generation propulsors to meet market-driven goals for noise (4 dB reduction) and efficiency (3-5% fuel burn reduction) *with integration effects*, relative to 2021 best-in-class propulsors, and reduce risk to a new single-aisle aircraft in the 2030's.

which can be broken down as:

- "Assess, model, and predict" — NASA has expertise in testing, modeling, and system-level predictions to assess aerodynamic performance and noise. NASA does not have the resources under EQuIP to design a fan so the TC leverages an existing public/private partnership under the FAA CLEEN program to assess state-of-the-art fans/propulsors.
- "market-driven goals" — the 4 dB noise reduction and 3-5% fuel burn reduction goals are based on many discussions with manufacturers and represent the minimum improvements required to make a viable product.
- "with integration effects" — experience shows that engine airframe installation has a significant effect on engine/propulsor performance. For example, a propulsor subject to inflow distortion will not be as efficient as one operating in a clean flow environment. The TC seeks to account for installation effects on the propulsor though simulations and measurements.
- "relative to 2021 best-in-class propulsors" — referring back to the "market-driven goals", improvement should be calculated from the current best-in-class propulsors, i.e. the GE LEAP1B and/or Pratt & Whitney GTF.
- "reduce risk to new single-aisle aircraft" — NASA has world-class expertise in acoustic liner design and aircraft icing. The EQuIP TC leverages these capabilities to seek additional acoustic margin and develop methods to evaluate unducted or ultra-short inlet ducted propulsors for icing risk.

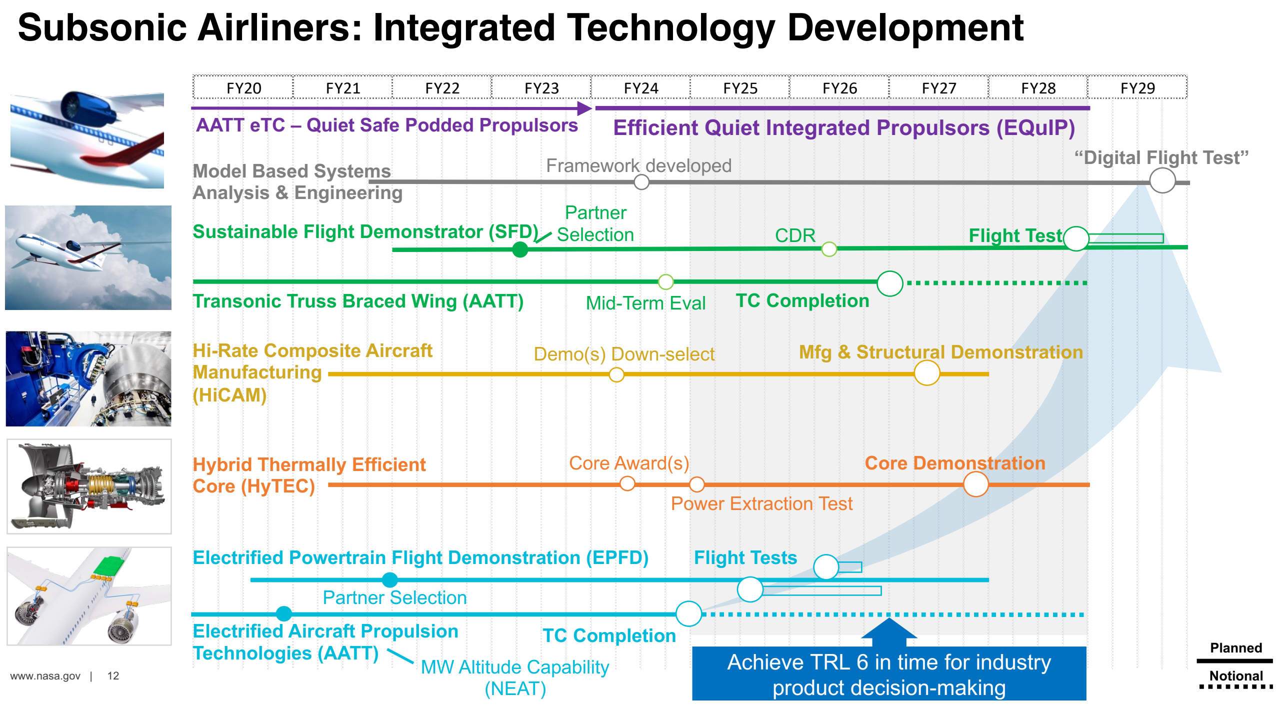



Figure 2 – Timeline of NASA subsonic airliners research portfolio.

- "in the 2030's" — targeting the SFNP goals; per the timeline in Figure 2, new technology needs to achieve TRL 6 by 2028 to allow time for development, integration, and certification before entry into service in the mid-2030's.

Note that the EQuIP TC goals statement does not specify that the next-generation propulsor will be ducted or unducted on the "market-driven goals" needed to produce a viable product. The TC statement recognizes that ducted and unducted propulsor have very different technical challenges but does not commit to a single configuration to meet the goals.

## 2.1 Plan Overview

Figure 3 shows the major components of work *as planned* to meet the EQuIP TC goals[5]. The plan includes a Key Decision Point (KDP) in Quarter 1 of fiscal year (FY) 2025 to define the Integrated Propulsor Test (IPT) based on results from the "Integrated Propulsor Test - Feasibility and Design Study". This approach allows time for the team to acquire isolated fan data, consider model and/or facility options, and engage potential partners that will maximize value for the IPT.
The two isolated propulsor tests (i.e. no wing/airframe) will quantify the propulsor performance, aeromechanics, and noise for a ducted and unducted fan while also providing flow data to validate the CFD. A unique six degree-of-freedom rotating balance will be used for the unducted fan test[6] to measure thrust and 1-P rotor loads at different angle of attack conditions. The isolated tests will use the 9x15 Low-Speed Wind Tunnel[7] (LSWT)/8x6 Supersonic Wind Tunnel[8] (SWT) complex at the NASA Glenn Research Center. These wind tunnels, with the NASA Ultra-High Bypass (UHB) and Counter Rotating Open Rotor (CROR) propulsor drive rigs, have been used regularly for ducted fan and unducted propulsor development since the 1980's (Figure 4). The 9x15 LSWT acoustically treated test section was refurbished in 2019 to reduce background noise in preparation for the next generation of quiet propulsors[2]. Data acquired will be used to validate the "Virtual" test results and support the IPT feasibility study and KDP.

[5]Planning follows the U.S. government's fiscal year (FY) that runs October 1 through September 30.
[6]This will be first six degree-of-freedom balance used for a fan test at GRC and its design and manufacture includes a significant R&D effort of its own.
[7]https://www1.grc.nasa.gov/facilities/9x15/ downloaded December 2023
[8]https://www1.grc.nasa.gov/facilities/8x6/ downloaded December 2023

NASA maintains expertise in fan noise prediction, particularly mid-fidelity methods that capture more physics than empirical models but at lower computational cost compared to LES. Each wind tunnel test is preceded by a "virtual" test to exercise and validate NASA's existing tools, methods, and simulations that predict the acoustics and aerodynamic performance (Figure 3). These "virtual" tests results are evaluated post-test using the test data acquired to estimate the prediction uncertainty and identify areas for improvement.

Acoustic liners (Figure 3) are designed for each test entry using any data available and simulated source distributions. These liners maybe built and tested in the next wind tunnel entry or evaluated using simulations depending on available resources. The NASA acoustic liners team has extensive experience designing and evaluating liners for ducted fans but unducted fan acoustic liners — external core nacelle, soft stators, pylon exterior — are a novel research area and predictions without experimental evaluation will necessarily have a higher uncertainty.

The ability to predict ice accretion on rotating machinery and then predict when that ice will shed are the key steps to mitigating the propulsor icing risk (Figure 3). The NASA "GlennIce" program is widely used to predict airframe icing. The EQuIP TC was planned to leverage data acquired for smaller UAM propellers to accelerate the development of a new tool for icing simulation and analysis of rotating machinery.

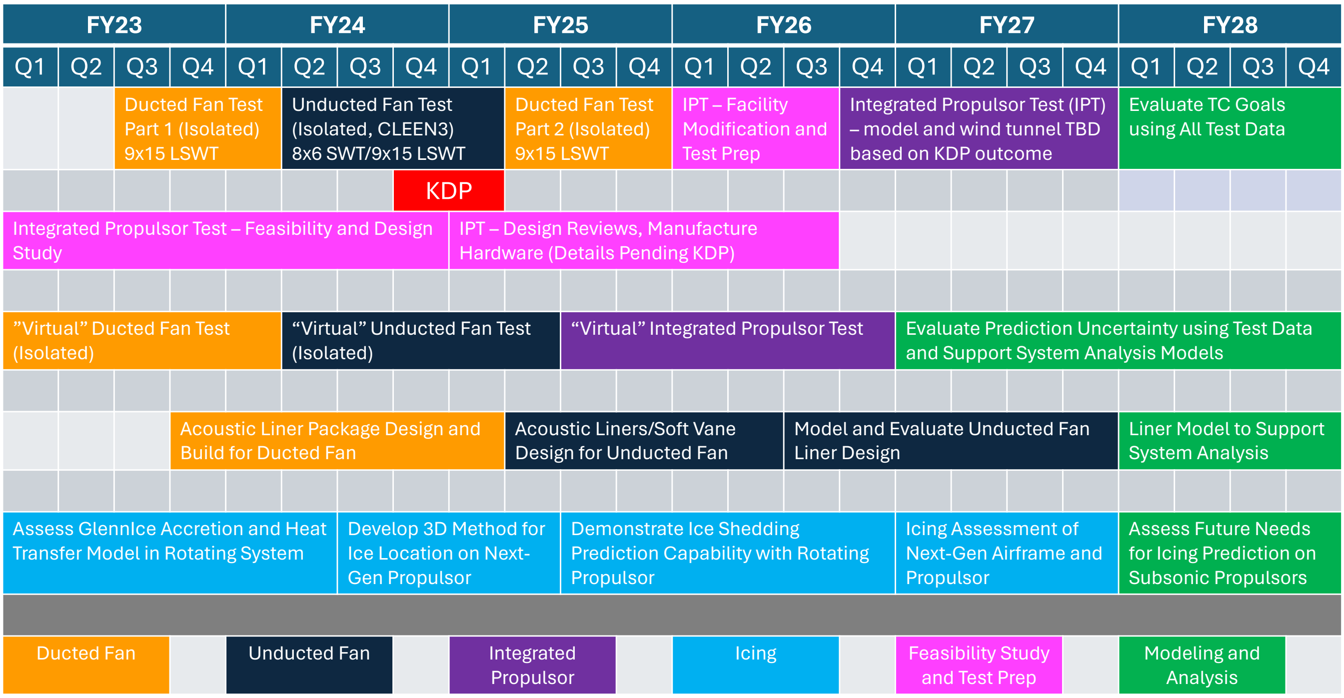



Figure 3 – Calendar of wind tunnel tests, "virtual" tests, and risk reduction activities planned for the EQuIP TC by fiscal year (FY, Oct. 1-Sept. 30).

## 3. EQuIP TC Feasibility and Design Study

The *minimum* EQuIP TC goals leverage recent investments in the 9x15 LSWT and propulsor drive rigs to study the operability, performance, and noise of the propulsor subject to the wing/airframe effects. The approach follows the methodology in [3] which describes independent development needs for the propulsor and the airframe before integrating them onto an aircraft. The EQuIP TC plan does not assume accurate wing/airframe data will be available due to the constrained size of the 9x15 LSWT test section. Successful completion of the TC will advance the propulsor TRL but require a future integrated propulsor-wing test to develop an efficient wing shape that accounts for the propulsor outflow. The EQuIP TC Feasibility and Design Study supports the KDP to determine the limits and value of this approach relative to the projected budget/resources. The KDP is also an opportunity to expand the scope to include propulsor-on-wing effects as potential partners and/or new resources emerge.


Figure 4 – Pictures from wind tunnel tests in the 9x15 LSWT dating back to the 1980's Un-Ducted Fan (UDF) test.

The feasibility study started in FY23 with a series of CFD simulations to:

- Estimate loading on a wing mounted in the tunnel; this gives the mechanical design team a starting point for the wing mounting system.
- Estimate tunnel blockage and maximum angle of attack possible with propulsor-wing model to establish limits on the test matrix.
- Analyze the effect of the 9x15 LSWT tunnel walls on wing model performance to determine if it is possible to acquire any meaningful airframe/wing performance data in this tunnel.

A representative fan-wing geometry was created by scaling the Source Diagnostic Test (SDT) fan[4] from 22"-diameter to 26"-diameter to account for the increase in bypass ratio between a circa-2000 propulsor and a 2030's propulsor. Next, the NASA Common Research Model High-Speed (CRM-HS) wing[9] geometry was scaled to approximately match the propulsor scale-factor. The propulsor and wing were then combined in the 9x15 LSWT test section to create the test configuration (Figure 5). The inlet nozzle and exit diffuser sections of the 9x15 LSWT were also modeled. These sections are important to determine maximum angle of attack where the fan starts ingesting boundary layer from the tunnel wall and/or the exhaust flow impinges on the tunnel walls.
SolidWorks Flow Solver[5] was used for CFD simulations to quickly estimate loads on the wing and tunnel blockage for the design study. It has automatic grid generation from a solid model and is relatively fast to run on a high-end desktop computer. An actuator disk model was used in place of the rotating fan to simulate the fan pressure rise to reduce computation time allowing more design iterations. Figure 6 shows sample results from these simulations of the full test section.

[9]The CRM wing geometries are described at https://commonresearchmodel.larc.nasa.gov

These simulations were also gave a quick estimate of the effect the tunnel walls have on the wing. Figures 7 shows the lift and drag produced by the wing at 4 angles of attack — $0$, $4°$, $8°$, $12°$ — as a function of propulsor thrust and Mach 0.1 flight (tunnel) speed in the tunnel. The lift force is dominant in each case but decreases as fan thrust increases and accelerates the flow on the underside of the wing. The lift and drag in each case is significantly reduced when the tunnel walls are removed. These results motivated additional simulations using the LAVA CFD package to build a more detailed analysis.

The Launch Ascent and Vehicle Aerodynamics (LAVA) code is a CFD package developed and maintained by NASA to provide a variety of mesh generation and flow solver methods suitable for a wide range of problems. The fan-wing-tunnel simulations utilized the high-fidelity curvilinear structured overset finite-difference solver within the LAVA framework[6], with Reynolds-Averaged Navier-Stokes (RANS) chosen as the turbulence closure method. Figure 5 provides global views of the LAVA computational domain, which consisted of 118 zones and approximately 43.2 million points at the production grid level. The LAVA solver employed the actuator disk approach with constant thrust loading to replicate the propulsor's effects on the overall flow field in both internal and external simulations.

Figure 8 compares the lift and drag forces on the wing computed using LAVA across a range of thrust-loaded systems, spanning from zero to seven kilonewtons (kN), and angles of attack both within the 9x15 LSWT and in free-air conditions. As expected, the active propulsion system alters the flow field around the wing section, generally reducing lift as thrust increases. The tunnel walls also increase the aerodynamic lift computed relative to the free-air simulations as observed in the SolidWorks simulations. Notably, the peak forces computed using LAVA are similar, for engineering purposes, to those determined using the SolidWorks Flow Solver allowing feasibility study to continue without a significant changes to the design requirements.

The streamlines depicted in Figure 9 show the flow patterns with varying propulsor thrust loading around the wing section at a $12°$ angle of attack. With increasing thrust loading, the propulsor captures a greater mass flow, causing the streamlines to bend further towards the center of the propulsion system, thereby reducing aerodynamic loads on the wing (in addition to the acceleration on the underside of the wing as discussed earlier). The streamlines in Figure 9 show that the flow separates on the suction side of the wing at $12°$ angle of attack for all thrust levels simulated. Figure 10 illustrates the size of the separation zone from the Yehudi break to the tip of the wing section over the wing suction side (depicted by the red coloration) at $12°$ angle of attack using the axial component of the skin friction coefficient. Notably, the flow over the suction side of the wing surface remained attached up to at least $8°$ angle of attack. However, Figure 10(c) shows the very beginning of a possible flow separation appearing at the wing tip indicating that angle of attack limit before separation is likely not much greater than $8°$. Finally, the LAVA simulations showed a complicated flow region at the wing/tunnel wall interface where variations in wing shape and/or the gap between the wing and tunnel wall can significantly change the flow separation on the wing. The best results were achieved with a gap that allows a wing tip vortex to form as shown in Figure 11; this finding is consistent with previous studies (e.g. [7]).

In summary:

- The wing at $12°$ angle of attack strongly separates on the suction side driving a sudden increase in drag.
- Wing flow separations at angle of attack are sensitive to the interface (or gap) between wing tip and top of the tunnel test section. Best results are achieved with a gap such that the wing tip is not in the wall boundary layer.
- The takeoff condition for a 26"-diameter fan at takeoff thrust could be a challenge for tunnel operations due to the large amount of induced flow in the test section.
- The 9x15 LSWT test section is too small for wing lift and drag measurements *at relevant propulsor scale* and, further, that the complex wing/wall flow interactions will make it difficult to model and correct for these wall effects.

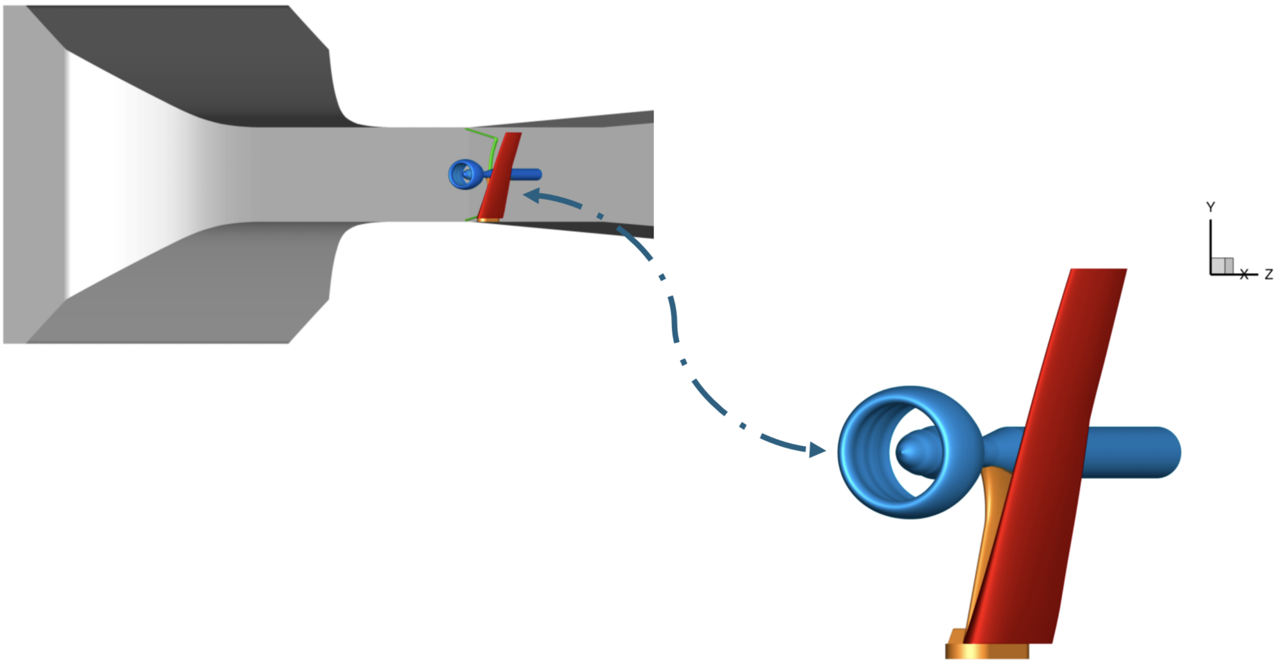



Figure 5 – Model of the 9x15 LSWT test section with UHB drive rig, 26"-diameter ducted fan, and notional wing based on the CRM-HS design.

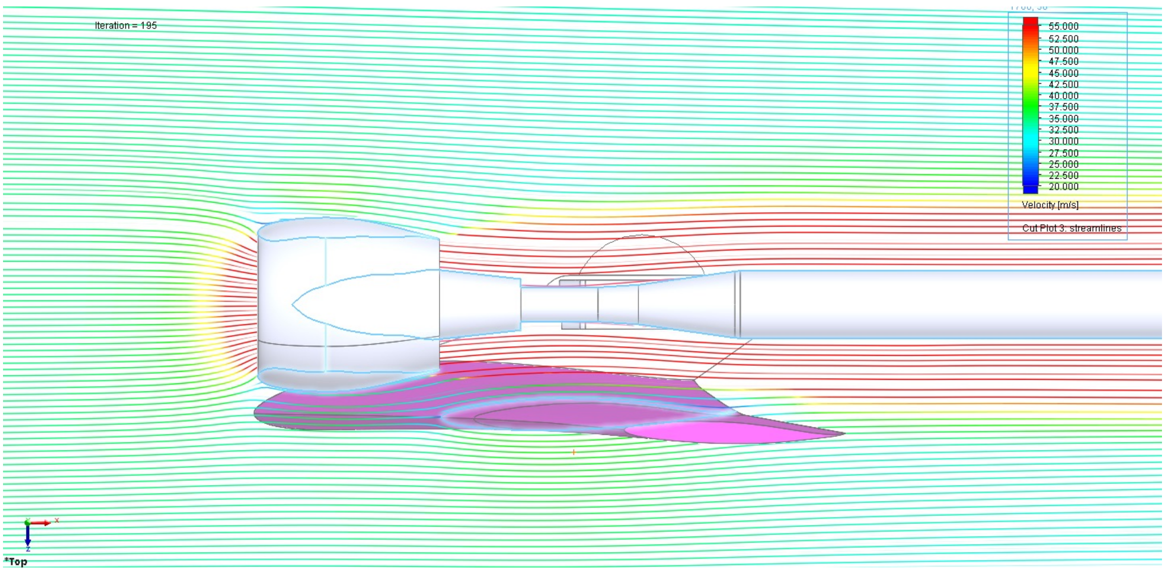
## 4. EQuIP TC - Summary and Next Steps

The Efficient Quiet Integrated Propulsor (EQuIP) Technical Challenge (TC ) officially began on October 1, 2023. These objectives of this TC were determined by sustainable aviation goals that include environmental, social, and economic needs. These objectives are reflected in the goals statement:

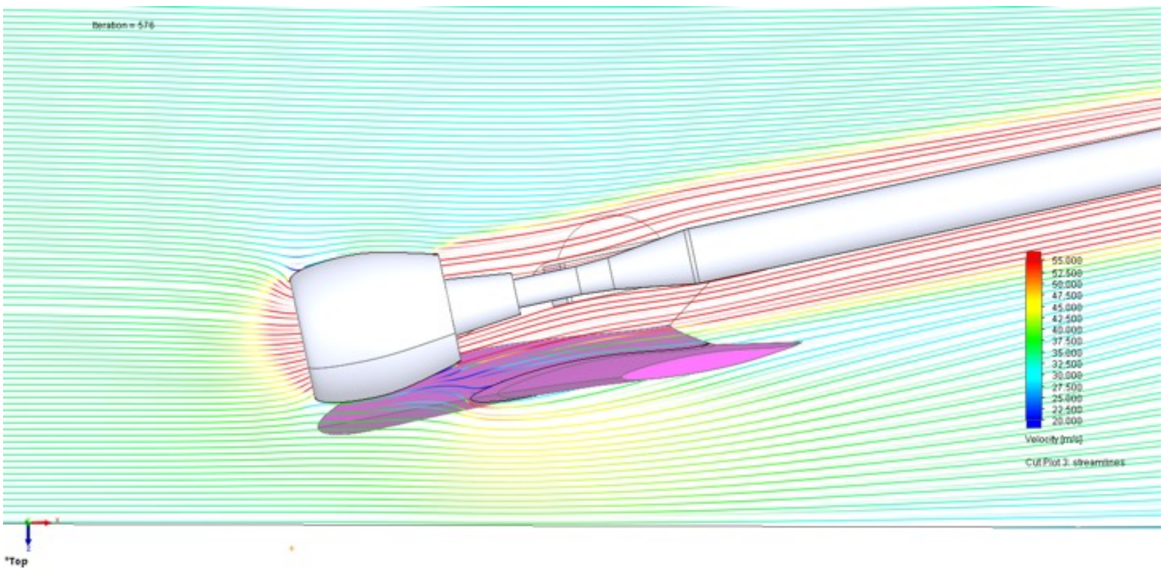
> Assess, model, and predict the ability for next-generation propulsors to meet market-driven goals for noise (4 dB reduction) and efficiency (3-5% fuel burn reduction) *with integration effects*, relative to 2021 best-in-class propulsors, and reduce risk to a new single-aisle aircraft in the 2030's.

These goals have a propulsor focus but recognize that the wing/airframe can not be neglected when designing a modern high-bypass ratio engine. A Key Decision Point (KDP), scheduled for October 2024, evaluate the results of a test feasibility and design study and consider technical options, potential partnerships, and any other opportunities to maximize the Integrated Propulsor Test scheduled for fiscal year (FY) 2027.

The Integrated Propulsor Test (IPT) is based on the premise that the aircraft propulsion and airframe systems can no longer be developed separately as in the past; the interaction effects imposed by the propulsor on the wing and by the wing on the propulsor are too strong in modern aircraft to separate development paths into wing/airframe and engine. This inseparable design criteria creates new challenges in mid-TRL development testing. Wind tunnel propulsor tests require a scale and power to be relevant to the full-scale engine (Reynolds number and tip Mach number are key factors). The minimum propulsor scale is generally higher than the required airframe/wing scale in wind tunnel test so that the propulsor sets the scale factor for an fully integrated propulsor-airframe test. However, there are very few wind tunnels in the world that can test a propulsor-wing system at the propulsor scale, provide sufficient power to the propulsor model, and drive test section Mach numbers to takeoff speeds. A survey of wind tunnels available to NASA, conducted as part of the feasibility and design study, found the 40x80-foot wind tunnel at the National Full-Scale Aerodynamics Complex at Ames Research Center (ARC), the 14x22-foot Subsonic Wind Tunnel at Langley Research Center (LaRC),

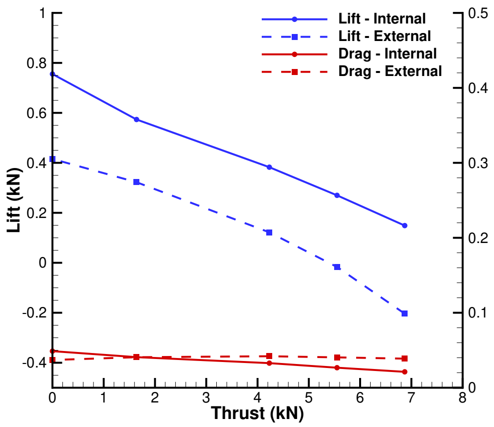



(a) AoA = 0

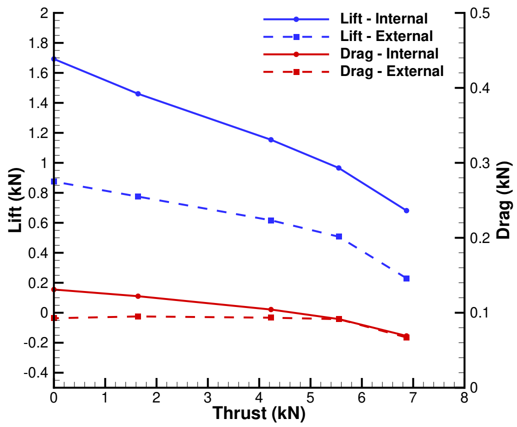



(b) AoA = $12^{\circ}$

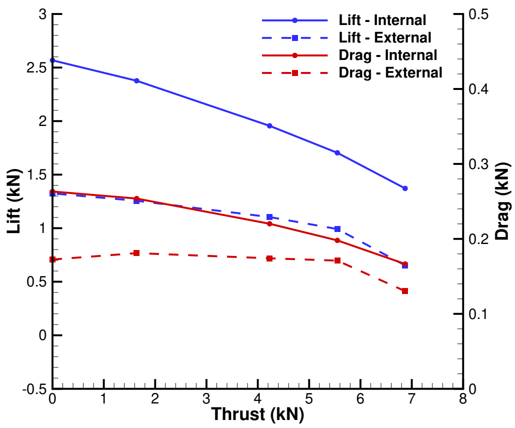
Figure 6 – Streamlines at Mach 0.1 tunnel speed and approach thrust computed using SolidWorks Flow Solver.



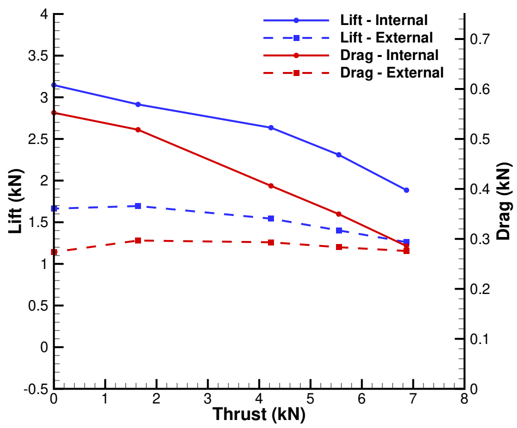

(a) AoA = 0




(b) AoA = $4^{\circ}$

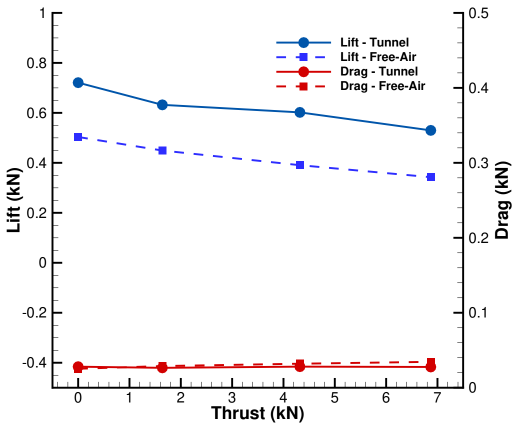



(c) AoA = $8^{\circ}$

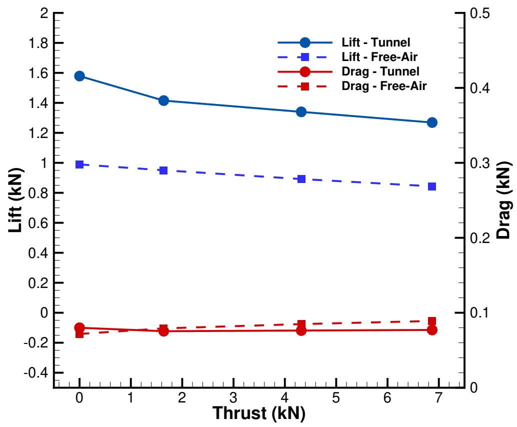



(d) AoA = $12^{\circ}$

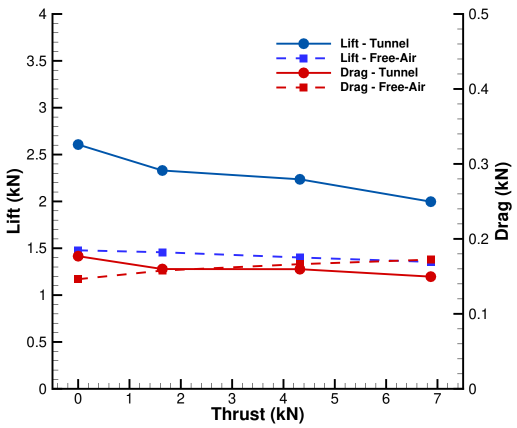
Figure 7 – Lift and drag forces on wing section as a function of propulsor thrust with ("Tunnel") and without ("Free-Air") tunnel walls in the simulation computed using SolidWorks Flow Solver.



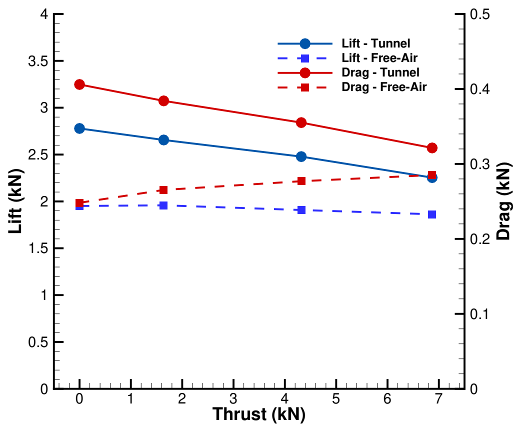

(a) AoA = 0




(b) AoA = $4^{\circ}$




(c) AoA = $8^{\circ}$




(d) AoA = $12^{\circ}$

Figure 8 – Lift and drag forces on wing section as a function of propulsor thrust with ("Tunnel") and without ("Free-Air") tunnel walls in the simulation computed using LAVA.

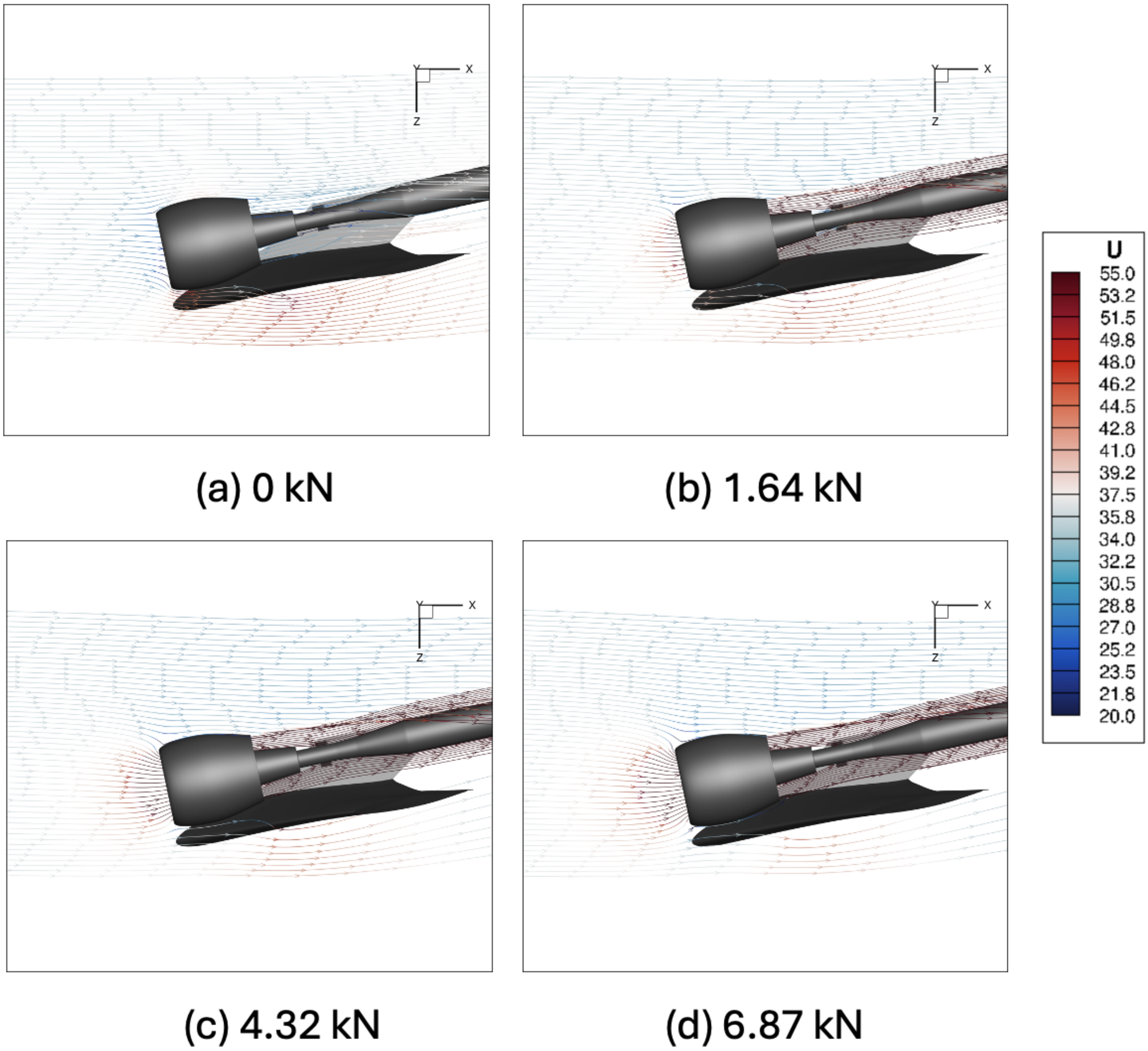



Figure 9 – Streamlines passing through the test section computed using LAVA at $12^{\circ}$ angle of attack and propulsor thrust loading of (a) 0 kN, (b) 1.64 kN, (c) 4.32 kN, and (d) 6.87 kN.

and the 9x15 LSWT at GRC possible destinations an integrated test. Each of these tunnels has advantages and disadvantages. For example, the 40x80 and 14x22 would need drive rig infrastructure but allow larger models while the 9x15 has drive rig infrastructure but limited size for an airframe model. The results of this survey along with the projected costs to move the propulsor drive, build a model, run the test, etc. will be used to inform the KDP.

The EQuIP TC will also support two isolated propulsor tests leading up to the IPT. Ongoing work to support these tests includes:

- Instrumentation to the turbine blades UHB propulsor drive rig to allow safe operation of a 26-inch ultra-high bypass ratio fan low-speed, high-torque corner of the UHB's design space[10].
- Modifications to the CROR propulsor drive rig to allow single rotor operation.
- Design and manufacture of a rotating telemetry system and a unique 6-component force balance on the forward rotor[11].

[10] Partially funded by NASA ARMD Capability Leadership Team (ACLT).

[11] Partially funded by NASA ARMD Capability Leadership Team (ACLT).

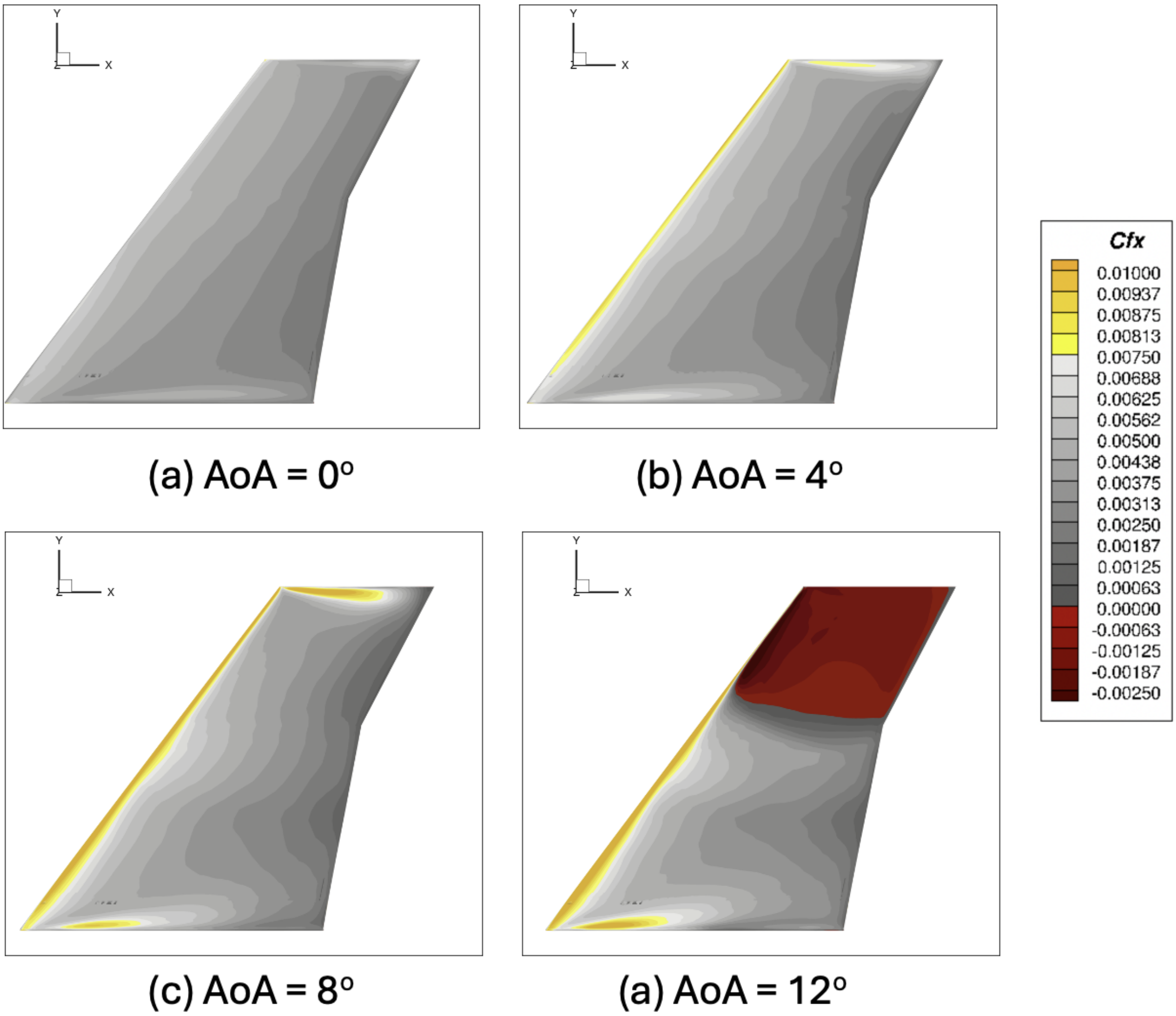



Figure 10 – Contours of the axial component of the skin friction coefficient computed using LAVA at (a) $0$, (b) $4^{\circ}$, (c) $8^{\circ}$, and (d) $12^{\circ}$ angle of attack.

- Modernizing the data acquisition and processing system to ensure it meets NASA and partner test requirements.

These tests will provide critical data to validate prediction tools and models that provide design guidance to design the IPT test hardware. Again, all available data will support the KDP to determine the scope of the IPT test.

The EQuIP TC address the effect of engine-airframe installation on the propulsor performance and noise. This is one of the two parts required for an integrated propulsor-airframe development program with the other being propulsor effect on wing performance. And while we continue to seek opportunities to expand the EQuIP TC to include both parts, the current plan will advance the propulsor technology towards a next-generation product. These advances complement NASA's existing Technical Challenges in Hybrid Thermally Efficient Cores, Hi-Rate Composite Manufacturing, Electrified Aircraft Propulsion, and Transonic Truss-Braced Wing contributing to a more socially, environmentally, and economically sustainable future for aviation.

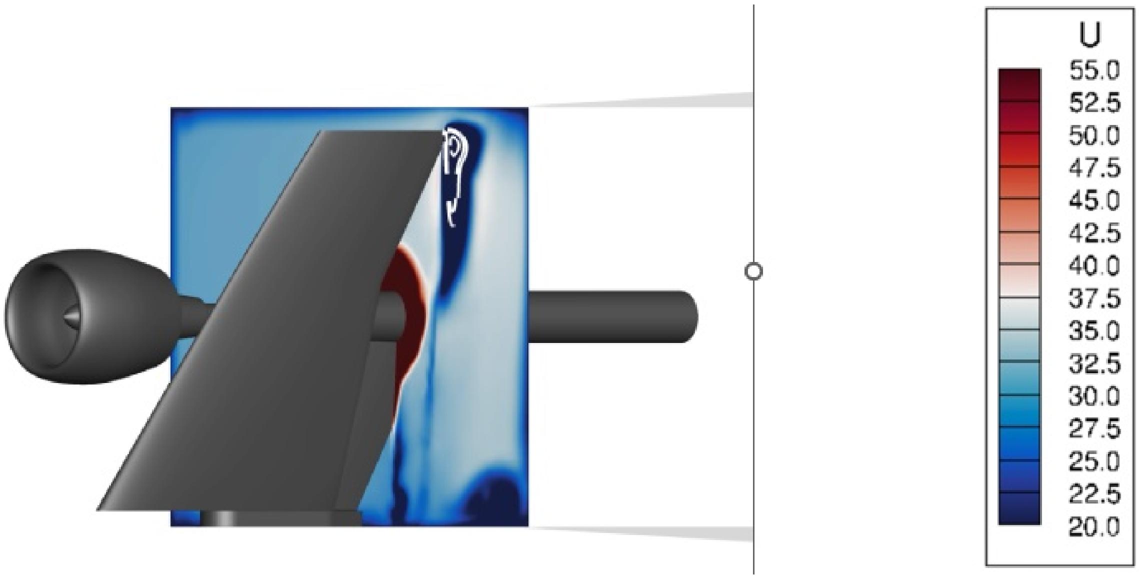



Figure 11 – Tip vortex in the region between the wing and tunnel ceiling form LAVA simulations.

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