Electrical Propulsive Fuselage Concept for Transonic Transport Aircraft

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ABSTRACT

NASA is broadly engaged in Electrified Aircraft Propulsion (EAP) efforts across air vehicle sizes and electric aircraft propulsion approaches. EAP enables a wide range of propulsion airframe integration options as well as the use of rechargeable energy storage in an aircraft. This paper is limited to a discussion of boundary layer ingestion (BLI) systems which are located on the fuselage of the aircraft and use electrical drive systems. We term that combination an "electrical propulsive fuselage". The benefits, challenges, and design parameters of an electrically driven fuselage BLI system are considered. Five existing types of fuselage BLI implementation approaches which can be implemented using either electrical or mechanical drive systems are reviewed. An overview of boundary layer types, fan response to boundary layer, and electrical system for aircraft propulsion is presented. An idea distributed electric propulsive fuselage is proposed.

Keywords: Electrified Aircraft Propulsion; Hybrid Electric; Boundary Layer Ingestion

1.0 INTRODUCTION

Recent interests in Electrified Aircraft Propulsion (EAP) have resulted in a number of turboelectric, hybrid, fully electric, mildly distributed, or highly distributed aircraft concepts [Bowman]. In addition, the technology of a propulsion system with boundary layer ingestion (BLI) has been significantly advanced through a number of analytical, computational, and experimental studies. An area of interest in electric BLI propulsion systems is to configure the aircraft with one or more electric propulsors such as ducted fans, open rotors, or propellers ingesting thick fuselage boundary layer flow at the tail section of the fuselage, which we term an Electrical Propulsive Fuselage. This paper proposes an idea for a distributed electric propulsive fuselage, which will require further investigation to determine potential merit.

2.0 BENEFITS, CHALLENGES & PARAMETERS

2.1 Benefits

The implementation of BLI systems on transport class aircraft has the potential to reduce fuel burn. BLI increases propulsive efficiency by ingesting lower velocity flow near the airframe into the propulsors, reenergizing the wake, and thereby reducing drag. BLI can be implemented on both conventional tube-and-wing as well as hybrid wing body (HWB) aircraft. The propulsor is mounted such that the slow moving flow near the aircraft is ingested, reenergized, and exhausted, replacing the aircraft wake with high momentum air.

Introduction of an electric drive system between the turbine and fan enables the decoupling of their speeds, and the areas of their inlet/outlet sections. With this approach, high bypass ratio (BPR) can be achieved since any number and size of fans can be driven from a single turbine. Increasing BPR results in improved propulsive efficiency. Also, the speed ratio between the turbine and the fan can be arbitrarily set and varied during operation, thereby removing the physical constraint levied by either direct shaft or geared coupling. As a result, the fan pressure ratio and the turbine/compressor ratios can also be optimized independently.

2.2 Challenges

Boundary layer ingestion poses challenges in both performance and integration. One performance issue arises from operating in a boundary layer - unlike operation in a free stream, under BLI conditions the fan blade will move through different flow speeds and angles as it moves through each rotation, causing a deficit in performance. In some cases, this effect can be reduced by the use of inlet guide vanes. Another performance impact results from the varied blade loading through a cycle, which causes fatigue cycling, and may require a thicker or differently designed blade to achieve the expected operating life. A more detailed discussion follows later in the paper.

BLI related integration challenges include the possibility of foreign object debris (FOD) ingestion, the impact on tail configuration, and fuselage integration impacts. Foreign object debris (FOD) ingestion is a consideration in any propulsion system implementation, boundary layer ingestion systems may be particularly susceptible to FOD problems in the case where the BLI fans are located towards the lower surface of the aircraft and aft of the landing gear. Some fuselage BLI systems have an impact on tail size or type; placement of the BLI fans on a tubular fuselage may necessitate a switch to a T tail implementation. In some cases BLI systems may provide flow over the tail surfaces during low speed operation, which could result in reduced tail surface area requirements. Frequently, the location of fuselage mounted BLI systems and their drive equipment coincides with location of other aircraft equipment in current designs; for example on a tube and wing implementation, the auxiliary power unit (APU) is located in the area where a BLI can may be integrated. Overall assessment of a BLI system at the aircraft level needs to account for the relocation of any displaced equipment. Structural impacts must also be considered, as the load from the thrust of the BLI system must be carried by the fuselage.

2.3 Design Parameters

In the next section, existing BLI concepts and new concepts presented here will be qualitatively ranked against a set of key design parameters. These design parameters are divided into two groups: those providing potential benefits, and those describing challenges. Design parameters related to BLI benefits include the maximum fraction of fuselage boundary layer that can be captured, and the size of the useful fan area. The design parameters related to BLI challenges are include the level of fan interaction caused by upstream disturbances, the likelihood of foreign object debris ingestion, the impact on tail configuration, and the fuselage integration impact.

3.0 REVIEW OF PROPULSIVE FUSELAGE IDEAS

Some conventional large transport aircraft have engines mounted either on the side, top, or tail section of the rear fuselage with inlets some distance away from the fuselage to avoid the ingestion of boundary layer flow generated by the long fuselage ahead of it. However, as shown by Smith [Smith] and Drela [Drela], the BLI propulsion system brings benefits in terms of increased propulsive efficiency of the propulsion system and reduction of aircraft thrust requirement through decreased drag of the aircraft. To illustrate various fuselage BLI propulsion system installation methods, five propulsion concepts are presented in Table 1 and described herein with more detail for each concept.

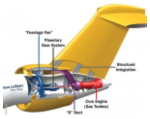
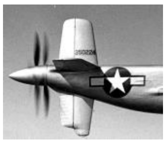
3.1 Ducted Full Circular

National Aeronautics and Space Administration (NASA) recently developed an electric propulsion aircraft concept called the single-aisle turboelectric aircraft with an aft boundary-layer propulsor (STARC-ABL) [Welstead] that features an electrically driven ducted fan at the tail cone section of the conventional fuselage aircraft to enhance propulsive efficiency by ingesting the fuselage boundary layer flow. The electric power needed by the ducted fan comes from two under-the-wing conventionally mounted turbofan engines coupled with high power electric generators. A similar BLI propulsor configuration was also recently proposed by Boeing on one of its Sugar Volt configurations [Boeing]. Bauhaus Luftfahrt suggested an aircraft configuration using mechanical propulsion systems, an advanced high bypass ratio turbofan engine installed at the fuselage tail cone section to ingest the circular fuselage boundary layer flow [Isikveren]. In all three of the above concepts, the ducted full circular propulsion system captures a significant portion of the circular fuselage boundary layer flow with a high bypass ratio ducted fan. Since the propulsion system is mounted at the tail section of the fuselage, the structure that supports the propulsor must also provide structure for the tail. In order to minimize structural interference between the propulsor and the aircraft control surfaces near the tail, all three aircraft employ “T-tail” geometries. Although the BLI ducted fan may increase the propulsive efficiency by ingesting the boundary layer flow, especially in cruise when the angle-of-attack or sideslip of the aircraft is very small, the circular inlet may experience highly distorted inflow at a high angle-of-attack or sideslip condition. Another drawback of this configuration is the possibility of foreign object debris (FOD) or water ingestion during the take-off or the landing phase of the mission, which may result in damages to the fan or nacelle.

3.2 Open Rotor Full Circular

Implementation of an open rotor or propeller propulsion system at the tail section of an aircraft is a configuration that has been around for many years. An early example of this type of configuration is the 1940s era Douglas XB-42 Mixmaster experimental bomber aircraft which featured two counter-rotating propellers at the fuselage tail to enhance vehicle performance. Another example is the more recent General Atomics Predator unmanned aerial vehicle (UAV) which features a single propeller at the fuselage tail section. A large transport concept using a tail mounted electric propulsor was studied recently in NASA’s Parallel Electric-Gas Architecture with Synergistic Utilization Scheme (PEGASUS) configuration [Antcliff]. This concept is configured as a regional fixed wing aircraft with two electric turboshaft engines installed under the wing, providing electric power to not only the tail propulsor but also to two wing-tip mounted electric propulsors, minimizing the induced drag of the aircraft. In this type of configuration, similar to the ducted full circular type, high propulsive efficiency by the

Table 1. Propulsive Fuselage Concepts

Design Parameter	**Ducted Full Circular**	**Open Rotor Full Circular**	**Side Mounted**	**Flat Top Mounted**	**Bifurcated**
Benefits					
Fuselage BLI Capture	Good	Great	Moderate	Moderate	Good
Fan Area	Good	Great	Good	Moderate	Good
Challenges					
Fan Interactions	Good	Great	Moderate	Poor	Poor
Foreign Object Ingestion	Poor	Poor	Poor	Great	Poor
Tail Configuration	Moderate (T-tail)	Moderate (T-tail)	Moderate (T-tail)	Moderate (Twin Tail)	Moderate (Twin Tail)
Fuselage Intrusion	Moderate	Moderate	Moderate	Moderate	Moderate
					
Electrical Implementation	STARC-ABL, Boeing Sugar Volt	PEGASUS	Boeing EAP single-aisle	N3-X	
					
Mechanical Implementation	Bauhaus Luftfahrt Propulsive Fuselage	Douglas XB-42	ONERA's NOVA	D8	

open propulsor can be achieved by ingesting thick circular fuselage boundary flow and filling the wake of the fuselage with high momentum air. However, a unique but undesirable feature of the tail-mounted open propulsor configuration is that the vehicle must not over-rotate during the take-off or landing phase of the mission, or the open propulsor blades may hit the runway and damage the propulsion system.

3.3 Dual Side Mounted

BLI aircraft concepts employing side mounted propulsion systems have been proposed to minimize certain issues associated with full circular fuselage BLI configurations, e.g. tail-strike impacts on the propulsion system, and FOD ingestion during the take-off or landing phases of the mission. , Boeing recently suggested a configuration using electric fans, employing two ducted fans on the left and right sides of the fuselage tail cone, which will still ingest a significant part of the fuselage boundary layer flow [Boeing]. A similar concept using mechanical ducted fans is also proposed by the Office National d'Etudes et de Recherches Aérospatiales (ONERA) on its NextGen ONERA Versatile Aircraft (NOVA) configuration [Wiart]. However, unlike the full circular BLI fuselage concepts, these configurations may experience high inlet distortion even at low angle-of-attack or sideslip conditions.

3.4 Flat Top Half

Several aircraft concepts studied by NASA and its contractors feature a BLI propulsion system on top of a relatively flat fuselage tail. In addition to improving propulsive efficiency, this configuration is intended to also reduce community noise by shielding the propulsion system noise with an airframe structure. One example is NASA's turboelectric distributed propulsion (TeDP) vehicle, N3-X, which features a number of electric ducted fans on the rear fuselage of hybrid-wing-body (HWB) airframe to ingest upper airframe surface boundary layer flow [Kim, Felder]. Power needed by these electric fans is supplied by two wing-tip mounted turboelectric generators. A recent system study indicated that this configuration may reduce the total mission energy usage by up to 72 percent relative to the current generation of similar size vehicles performing the same mission [Kim, et al.]. For the evaluation of noise, two variants of this configuration were examined, one with wing-tip turbo-electric generators and the other with turboelectric generators completely embedded inside the airframe [Berton]. The first configuration is estimated to have a International Civil Aviation Organization (ICAO) Chapter 4 cumulative margin of 32EPNdB, while the second configuration is estimated to have a margin of 64EPNdB.

A vehicle concept employing a mechanical version of this BLI propulsion system was proposed by the Massachusetts Institute of Technology (MIT) under a NASA Research Announcement (NRA) [Greitzer et al.]. This concept, called the D8, features a double-bubble fuselage cross section and two ducted fans installed between two vertical tails to ingest the upper fuselage boundary layer flow. A recent experimental study indicates that this configuration provides an 8.6% benefit in terms of mechanical power requirement compared to a similar aircraft with a non-BLI configuration [Uranga].

3.5 Bifurcated

Another BLI concept featuring a relatively flat fuselage tail surface employs bifurcated inlets at the fuselage tail section. Since the inlets capture both the top and bottom surfaces of the fuselage boundary layer flow, the propulsive efficiency of this BLI configuration can be greater than that of a one-sided propulsion system (e.g. the N3-X and the D8). However, because the fans will ingest not only the upper surface boundary layer flow but also the lower surface flow, the propulsion system may experience greater inlet distortion level, and may also ingest FOD or water during the take-off or landing phases of the mission. Due to the uncertainty of ingesting asymmetric fuselage inviscid and boundary layer flows, this type of configuration has not been studied in detail, but may provide additional propulsive efficiency benefits if these problem areas are addressed.

4.0 BOUNDARY LAYER TYPES

A Boundary Layer Ingestion system must deal with distortion in the air stream, which is divided into two categories, Type I distortion and Type II distortion. The Type I distortion, also known as 180-degree distortion, is characterized primarily by a circumferential distortion in which the boundary layer being ingested into the inlet occupies a portion of the lower part of the inlet for a top mounted system. The Type I distortion flow is characterized by dividing the flow state at the nacelle inlet area into 2 regions – clean inflow and distorted inflow. An example of a Type I distorted flow is shown in Figure 1, in which the colors represent levels of total pressure. The majority of the flow, shown in blue, represents a clean inflow characterized by constant total pressure and no swirl (no circumferential flow angle). This is the flow state at which today's propulsors are designed to operate, i.e. are highly efficient and have a wide operating range. The clean flow state is the largest region of this inlet, and comprises 60% of the inlet area; it occupies the upper portion of the inlet due to the nacelle configuration on the fuselage. The bottom portion of the inlet, however, is the distorted flow state, resulting from the boundary layer generated by the fuselage being ingested into the nacelle by the fan. It is characterized by low total pressure and a large amount of swirl which can vary from -30° to +30°. The current fan design flying in today's engines is not designed to operate under this variation in swirl angle and variation in total pressure. Additionally, the fan will experience this distorted flow state continually, with each revolution, and must be designed to withstand the additional aeromechanic stresses imposed by the inlet flow. Due to the large variation in swirl, the fan blade may experience stall as it rotates through the distorted flow state, then recover when it enters the clean flow state each time it completes a revolution. If the fan isn't designed properly for this unsteady load variation through the distorted flow region, it could potentially fail. The first Type I distorted fan was designed and fabricated by United Technologies Research Center under contract to NASA at Glenn Research Center, and tested in NASA Glenn's 8x6 test facility at high-speed undergoing the flow state shown in Figure 1 [Arend]. The test was successful, and demonstrated that a fan can be designed and built to withstand the distorted flow state of a Type I distortion. However, the fan's efficiency was lower than optimal due to safety concerns; performance was sacrificed to enable increased blade strength so that the fan could withstand the distorted flow state.

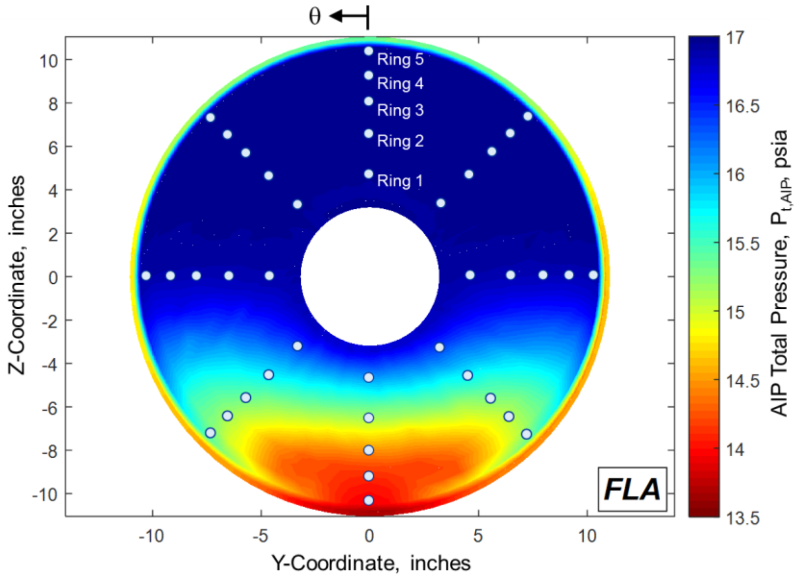


Figure 1. Example Total Pressure Distribution for a Type I Distortion

The Type II distortion, known as 360-degree distortion, is characterized by a radial profile in which the ingested boundary layer is derived from the flow around the fuselage for an aft mounted system. The expected distortion for a Type II configuration is completely different than that in a Type I system, and a fan built for Type I would not work on Type II. There is very little published data on what a Type II distortion at the nacelle inlet looks like, but its features can be surmised from knowledge of the boundary layer development. We start by considering an axisymmetric body of revolution devoid of wings and tail; under these conditions the boundary layer would be characterized by low total pressure at the near wall, increasing to free stream at the edge, and constant thereafter. This boundary layer would be axisymmetric in nature due to the geometry chosen, and the swirl angle, due to the absence of a mechanism to impart a circumferential flow component, would be zero. But a fuselage is not an axisymmetric body of revolution; thus the total pressure would not be axisymmetric but would be characterized by lower total pressure near the hub. The swirl, likewise, would be low but not zero due to up-wash from non-axisymmetric variations in the fuselage shape. Additionally, the wings and tail would have contributions: the flow would have a once-per-rev component due to the tail, and a two-per-rev component due to the wing adding to the swirl and low hub total pressure. Thus the flow can be characterized by an axisymmetric component due to the fuselage, and non-axisymmetric components due to the wing and tail. To determine the efficacy of a BLI system under Type II distortion, NASA is in the process of setting up a high-speed test of a tail cone thruster application through a subproject under its Advanced Air Transport Technology project. The objective of the challenge is to determine the fuel burn benefits of a tail cone thruster application relative to a baseline aircraft. The results of this test should show that the Type II benefits exceed that of Type I, based on the projected analysis studies by Smith [Smith].

5.0 FAN RESPONSE TO BOUNDARY LAYER

The two types of BLI distortion described above have very different impacts on the fan blades. A well-designed fan blade under completely clean inflow typically derives most of its efficiency at the tip. However, as was described above, Type I distortion causes the fan blade to experience drastically varying loads as it rotates around the centerline due to the air flow characteristics. The fan blade under a severe Type I distortion could be operating near design in the clean flow area, then stall as it travels through the boundary layer, repeating each revolution. This was evident in the BLI2DTF test [Arend] which was run in the 8x6 wind tunnel at NASA Glenn Research Center. The variation in flow and loading on the fan blade can cause serious aeromechanic issues, necessitating a more structurally sound blade design. Thus designing a fan blade for a Type I distortion results in a less efficient design, as evidenced in the published performance of the BLI2DTF test. One possible solution is to strengthen the tip region by locking the tips together, preventing them from dynamically vibrating during operation.

The fan blade for a Type II distortion does not require the same structural design requirement as that for a Type I flow, if the variation in radial distortion intensity is small. It is not expected to suffer the same performance penalties as a fan designed for operation under Type I distortion. However, due to the low total pressure in the hub region, the designer needs to radically change the hub design in order to get work out of the fan near the root. The outer portion of the fan should be efficient, but will be challenged by the non-axisymmetric components of the distortion, i.e. the swirl variations due to the tail and wing. The remedy for this design challenge is to design an inlet guide vane (IGV) that filters out these components and provides an axisymmetric total pressure profile to the fan;an exit guide vane (EGV) is then used to turn the flow back to axial. The IGV and EGV introduce losses to the system, thus reducing the overall efficiency of the system, but are needed to structurally support the nacelle and the exit nozzle, respectively.

6.0 ELECTRICAL POWER SYSTEM

Research in the electrical power area is focused on building lightweight, high-efficiency motors and power converters in the megawatt class [Jansen]. Megawatt-level components were selected because they support the implementation of partially turboelectric and hybrid electric propulsion up to the single-aisle aircraft class, and fully turboelectric or hybrid electric systems for smaller aircraft. While specific powers several times larger than those of industrial motors have long been recognized as key requirement, more recently the system benefits of the combination of high specific power and high efficiency have become clear. NASA-sponsored efforts to develop megawatt-class motors are ongoing at the University of Illinois (1 MW) and at The Ohio State University (up to 10 MW), and a 1.4-MW motor is being designed at NASA Glenn Research Center.

Power converters are an essential component in most EAP aircraft concepts, for generating the required electric power, and for driving the electric motors. Because they are a major contributor to the powertrain’s weight, NASA is sponsoring three inverter (DC to AC converters) efforts at the 1-MW-size class. For these efforts, 1000 and 2400 V DC input voltages are assumed, each with a three-phase AC output, in order to address the power conversion typically required to feed an electric motor in advanced EAP concepts for large airplanes. Although present aviation power systems are restricted to a maximum voltage level of 540 V DC (□270 V), these development efforts target higher bus voltages in recognition of the positive benefit of increased voltage on the overall size and weight of the powertrain. As an example, to deliver 1 MW over 150 fee, increasing the voltage form 540V to 2000 V can reduce the DC cable weight from 900 to 200 kg.

Two efforts are underway to develop power converters with high specific power (target of 19 kW/kg) using traditional liquid cooling technology: General Electric (GE) is building a three-phase inverter using SiC power electronics, and the University of Illinois is building a 200-kW multilevel inverter (which supports scaling to the 1 MW level) using gallium nitride switches. Additionally, in support of aircraft concepts with available cryogenic fluids (e.g., N3–X and SUGAR Freeze), Boeing is developing a cryogenically cooled inverter with a goal of 26 kW/kg and an efficiency greater than 99.3 percent, and has conducted a fairly extensive set of cryogenic power switch characterization tests to understand the impact of low temperatures on the switch performance.

7.0 DISTRIBUTED ELECTRIC PROPULSIVE FUSELAGE IDEA

We propose a distributed electric propulsive system for tube and wing aircraft (Figure 2). In this system a large number of fans would be distributed around the aft end of the fuselage to capture and reaccelerate the boundary layer. The fans would be electrically driven, making optimally placement (to capture the most important portions of the fuselage boundary layer) relatively simple. Several design options which have yet to be explored include placement of the distributed fan system, the design of integrated fuselage, inlet, and fan, and the integration of the fan and electrical drive.

Some of the factors affecting circumferential placement of the BLI fans along the fuselage include: location of the largest boundary layer, location to reduce the likelihood of FOD ingestion, and implications due to tail strike. For the propulsive fuselage to have a net benefit, a balanced approach to designing the fuselage, inlet, and fan system needs to be used; independent selection of the maximum performance approach for each element is unlikely to result in the highest performance integrated system. Two options which can be considered include the use of individual fan pods as depicted in Figure 2, or use of a "mail slot" approach where all of the fans are integrated into an inlet system that spans across the collective group. This design process may require advancements in the tools and techniques used for designing integrated propulsion airframe systems. Finally, the fan and electrical drive integration needs to be considered; two alternatives here are to drive the fan from an internal hub with an electric motor, or to drive the fan at the rim with a motor located somewhere in the duct.

We consider this concept to be a distributed propulsion version of a propulsive fuselage closeout that is enabled by the use of electric machines to drive a large number of fans.

Figure 2. Distributed Propulsive Fuselage on Tube and Wing

Table 2. Distributed Propulsive Fuselage Attributes

Design Parameter	Value
Benefits	
Fuselage BLI Capture	Moderate
Fan Area	Moderate
Challenges	
Fan Interactions	Poor
Foreign Object Ingestion	Moderate
Tail Configuration	Good (possible thrust vectoring)
Fuselage Intrusion	Good

An enabling feature of the electric machine in this configuration is that the many fans do not need mechanical linkages to the power source. Another important feature is that electrically driven fans can be independently controlled, allowing optimization of the boundary layer ingestion, and the possibility of some degree of thrust vectoring.

Our initial assessment of this idea against our design parameters is shown in Table 2. The potential fuselage BLI capture is notionally related to the fraction of the circumference spanned by the distributed fans. The Moderate performance rating on fuselage BLI capture is meant to indicate that that capture area is less than a fully circumferential system, but still significant. The Moderate fan area rating indicates that the fan area which could be captured is significant in comparison to the underwing turbofan area. Fan interactions in this system are rated as Poor, because they generate Type I distortion, with the associated challenges. FOD is rated Moderate because the fans on the bottom of the aircraft have been eliminated, reducing the FOD likelihood; however the fans on the side of the fuselage are still relatively low to the ground. The tail configuration is rated Good because it may be possible to implement this system with a standard tail approach, and there is some potential for thrust vectoring. Fuselage intrusion is rated Good because it may be possible to implement this system without significant repositioning of equipment currently located in the tail section of the fuselage.

8.0 CONCLUSION

This paper proposes an idea for a distributed electric propulsive fuselage, which would require further investigation to determine its potential merit. This configuration is intended to address concerns for the placement of a boundary layer ingestion system on a tube and wing aircraft. Specifically, it may reduce the likelihood of FOD or tail strike, reduce integration space concerns, and enable some thrust vectoring. Significant future work would be required to evaluate this idea in terms of aircraft level fuel burn and noise impacts. Trade studies would be required to narrow down to a preferred initial investigation configuration, followed by aircraft level system concepts studies to investigate fuselage intrusion, FOD likelihood, and tail size impacts. Also fan, inlet, and electrical drive studies would need to be conducted to investigate the possible approaches and down select a preferred concept.

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