DISTRIBUTED PROPULSION VEHICLES

Hyun Dae Kim
NASA Glenn Research Center
Cleveland, Ohio, USA

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Abstract

Since the introduction of large jet-powered transport aircraft, the majority of these vehicles have been designed by placing thrust-generating engines either under the wings or on the fuselage to minimize aerodynamic interactions on the vehicle operation. However, advances in computational and experimental tools along with new technologies in materials, structures, and aircraft controls, etc. are enabling a high degree of integration of the airframe and propulsion system in aircraft design. The National Aeronautics and Space Administration (NASA) has been investigating a number of revolutionary distributed propulsion vehicle concepts to increase aircraft performance. The concept of distributed propulsion is to fully integrate a propulsion system within an airframe such that the aircraft takes full synergistic benefits of coupling of airframe aerodynamics and the propulsion thrust stream by distributing thrust using many propulsors on the airframe. Some of the concepts are based on the use of distributed jet flaps, distributed small multiple engines, gas-driven multi-fans, mechanically driven multi-fans, cross-flow fans, and electric fans driven by turboelectric generators. This paper describes some early concepts of the distributed propulsion vehicles and the current turboelectric distributed propulsion (TeDP) vehicle concepts being studied under the NASA's Subsonic Fixed Wing (SFW) Project to drastically reduce aircraft-related fuel burn, emissions, and noise by the year 2030 to 2035.

Nomenclature

ADP	aerodynamic design point
CAEP	Committee on Aviation Environmental Protection
CESTOL	cruise-efficient short take-off and landing
CFF	cross flow fan
C_L	lift coefficient
eBPR	effective bypass ratio
FPR	fan pressure ratio
HWB	hybrid-wing-body aircraft
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
OPR	overall pressure ratio
RTO	rolling take-off
SBIR	Small Business Innovative Research
SFW	Subsonic Fixed Wing Project
SHP	shaft horse power (1 SHP ~0.746 kW)
STOL	short take-off and landing
TeDP	turboelectric distributed propulsion
TRL	Technology Readiness Level
TSFC	thrust specific fuel consumption
UAV	unmanned aerial vehicle.

1 Introduction

NASA has been investigating distributed propulsion concepts applied to future aircraft under the Subsonic Fixed Wing (SFW) Project. In response to growing aviation demands and concerns about the environment and energy usage, the SFW Project identified four 'corners' (goals) of the technical trade spaces—fuel burn, emissions, noise, and field length—for future aircraft design. Table 1 lists these technology goals for three future time frames, where N+1, N+2, and N+3 represent achieving a "Technology Readiness Level" (TRL) [1] of 4 to 6 by years 2015, 2020, and 2025 respectively. Although it may not be feasible to meet all the goals for each time frame, the multi-objective studies will attempt to identify possible vehicle concepts that have the best potential to meet the combined goals. To improve vehicle

Table 1. NASA subsonic transport system level metrics.

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metroplex* concepts

*** Technology Readiness Level for key technologies = 4-6
** Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

performance in meeting NASA's N+3 goals, drastic changes in propulsion and airframe systems are required and proposed. One such proposed concept is based on a distributed propulsion system using advanced electric power generation and transfer of power to remotely located distributed electric fans. This concept is called turboelectric distributed propulsion (TeDP). Because this revolutionary propulsion concept may provide such high performance and the possibility of meeting the N+3 goals, some previous and current research activities in the area of distributed propulsion study are presented as background for the TeDP concept.

2 Types of Distributed Propulsion

A number of fixed wing aircraft using 'distributed propulsion' have been proposed and flown before. Because what constitutes distributed propulsion for aircraft is not clearly defined—any aircraft with more than one propulsor could be classified as such—the following description is applied to further reduce the number of possible vehicle configurations:

"Distributed propulsion in aircraft application is the spanwise distribution of the propulsive thrust stream such that overall vehicle benefits in terms of aerodynamic, propulsive, structural, and/or other efficiencies are mutually maximized to enhance the vehicle mission."

Based on the above description, specific concepts qualified to be examined further for application in distributed propulsion aircraft design are explained below.

2.1 Jet Flaps

The jet flap is a concept where a high-velocity thin jet sheet emanates from a tangential slot at or near the wing trailing edge and provides spanwise thrust for cruise and supercirculation for high lift around the whole wing section during take-off and landing. One such research aircraft utilizing this concept was the Hunting H.126 aircraft, shown in Fig. 1, that was built and flown in the 1960's at lift coefficient $C_L = 7.5$ and maximum operationally usable $C_L = 5.5$. To enable such high lift, the engine diverted almost 60% of its thrust across its wing trailing edge to achieve very high lift capability.

Fig. 1. Hunting H.126 jet flap aircraft.

2.2 Cross-Flow Fan

The cross-flow fan (CFF), or transverse fan, is a two-dimensional spanwise propulsor that is integrated within a wing structure to distribute the thrust along the wingspan. Fig. 2 shows one such configuration where the fan ingests the wing upper and lower surface boundary layer air and ejects the air at the wing trailing edge [2]. In this configuration, two gas generators mounted at the wing root and the wing tip transmit the power to the CFF rotors that are placed near the wing trailing edge and connected by flex-couplings or universal joints. However, because of low performance of the fan and difficulty of installation within an aircraft wing structure, this transport concept was never put into practice.

Recently the CFF concept has been studied in more detail [3,4], and fan efficiency has been improved using computational fluid dynamics (CFD) technique. Some of the current CFF technology applications are proposed in personal air vehicles (PAV) and unmanned aerial vehicles (UAV). Fig. 3 shows a UAV flight demonstrator concept using the CFF as a propulsor [5].

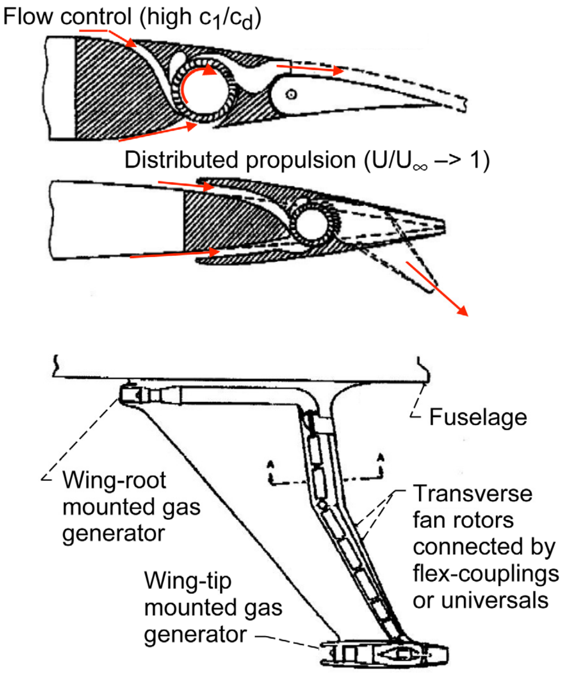

Fig. 2. A cross-flow fan (CFF) transport concept ingesting top and bottom sides of boundary layer flow [2].

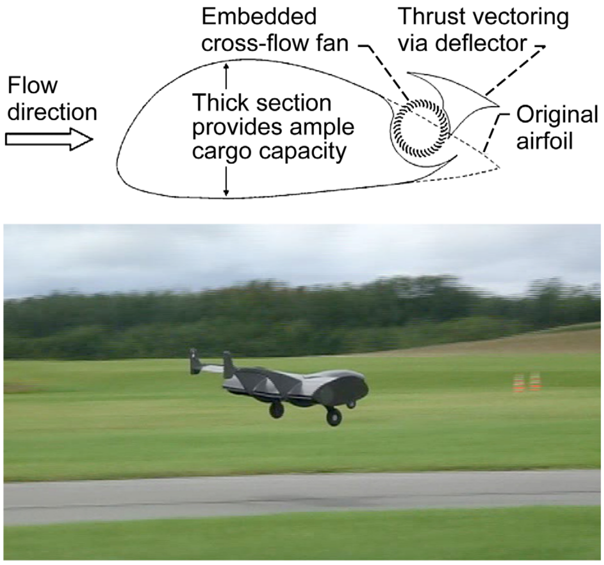

Fig. 3. A cross-flow fan (CFF) unmanned aerial vehicle (UAV) model in flight [5].

2.3 Multiple Discrete Engines

Various types of aircraft using multiple propulsors have been proposed and flown. For these aircraft, propulsors such as propellers, turbojets, or turbofans are mounted in front of the wing, at the back of wing, or within the thick section of wing. Although the number of propulsors required to be considered as distributed propulsion for a vehicle is not clearly defined, one can consider the 1940's YB-49 flying aircraft as an example. It had four linearly arranged conventional turbojet engines in each side of wing with subsonic rectangular inlets at the leading edge and conventional circular nozzles at the trailing edge of the wing.

Recently, a cruise-efficient short take-off and landing (CESTOL) aircraft was proposed (Fig. 4) based on a high subsonic hybrid wing body (HWB), or blended wing body (BWB), transport configuration because of its high cruise efficiency, low noise characteristics, and a large internal volume for integrating embedded distributed propulsion system [6]. The propulsion system employed 12 small conventional engines partially embedded within the wing structure and mounted along the wing upper surface near the trailing edge to enable short take-off and landing (STOL) operation using low-pressure-fan diverted-bypass air. The vehicle concept uses distributed propulsion for

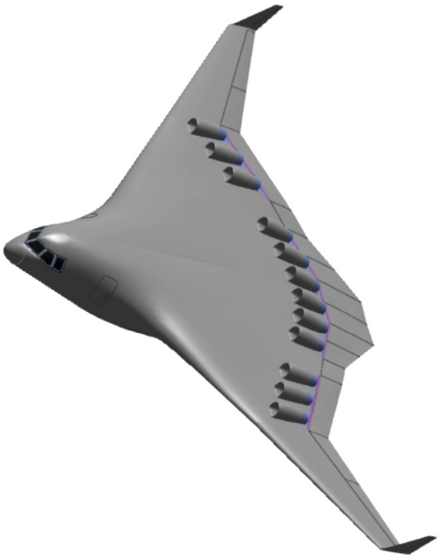

Fig. 4. Cruise Efficient Short Take-Off and Landing (CESTOL) configuration using twelve discrete engines partially embedded in the airframe [6].

quiet powered lift using an internally blown flap, with substantial engine noise shielding effect by the airframe, rapid climb out, and steep descent approach to provide a very low noise footprint on the ground. These characteristics of the aircraft may enable 24-hour use of the underutilized regional and city-center airports to increase the capacity of the overall airspace while still maintaining efficient high subsonic cruise flight capability.

2.4 Distributed Multi-Fans Driven by Few Engine Cores

Distributed propulsion employing multiple propulsors driven by a few fuel-efficient engine cores has been studied and is being pursued under NASA's SFW N+3 project. Under this category, three types of propulsion system are identified and described below.

2.4.1 Gas-Driven Multi-Fans

In the late 1960's, a vertical/short take-off and landing (V/STOL) air-deflection and modulation (ADAM III) fighter concept shown in Fig. 5 was studied for various missions, but the design never went into production possibly because of the problem of ducting hot gas through the wing structure. [7] In this concept, the gas generators and their inlets were installed near the fuselage to provide hot gas to the wing mounted turbines that drove high-bypass-ratio turbofans. The turbofans and turbines were co-located in the wing section away from the gas generators. The hot gases from the gas generators were routed through long ducts across the wing span to the location where the turbines and fans were installed. The inlets and nozzles for the turbofans and turbines were also all within the wing structure away from the gas generators and provided distributed thrust to the vehicle.

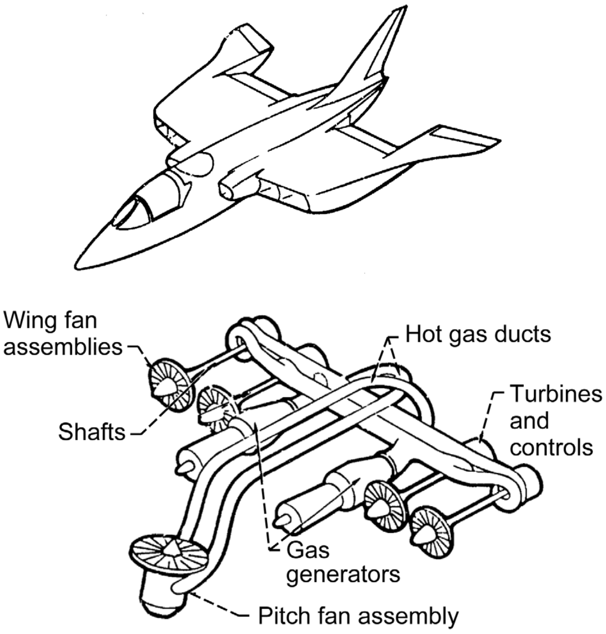

Fig. 5. ADAM III fighter configuration using gas driven multi-fans propulsion system [7].

Fig. 6. Short take-off and landing STOL transport using low compressor discharge tip-driven multi-fans [8].

Then in the 1970's, a gas-driven multi-fan transport aircraft was conceived, and a model was tested for STOL operation. The aircraft shown in Fig. 6 was based on a conventional 'tube and wing' airframe configuration with 16 tip-driven fans spread along the top surface near the wing trailing edge [8]. The tip-driven fans with fan pressure ratio of 1.25 were powered by high-pressure discharge air from the low-pressure compressor stages and mounted on a hinged flap to achieve high lift via supercirculation. In addition, the massive suction effect in front of inlets created additional lift on the airframe and delayed flow separation on the wing upper surface.

2.4.2 Gear-Driven Multi-Fans

A distributed propulsion concept employing a dual fan driven by one engine core on a HWB airframe was recently studied by NASA [9]. The study was to determine the effects of a dual-fan engine configuration on the vehicle-level performance (i.e., range) of a representative subsonic transport and to develop a preliminary understanding of the challenges associated with the implementation of distributed propulsion schemes. The Fig. 7 shows one such concept where an engine core drives two large-diameter fans via gears and shafts, providing a very high bypass ratio. In this configuration, the core engine is outside the airframe boundary layer flow with almost 100% inlet total pressure recovery, and the dual fan ingests full boundary layer flow approaching the inlet cowl lip.

For the Silent Aircraft Initiative, the Cambridge-MIT Institute developed the SAX-40 conceptual HWB aircraft using a similar gear-driven multi-fan propulsion concept [10–12]. The purpose of this study was to design an aircraft with noise being the primary design variable addressed, such that the noise would be contained within the perimeter of an urban airport. This aircraft, shown in Fig. 8, employs three engine nacelles where each nacelle houses three fans that are connected to a single engine core through gears and shafts. Similar to NASA's study, this propulsion concept also has a very high bypass ratio and low engine noise. Also, it features inlets with a high amount of airframe upper surface boundary layer ingestion.

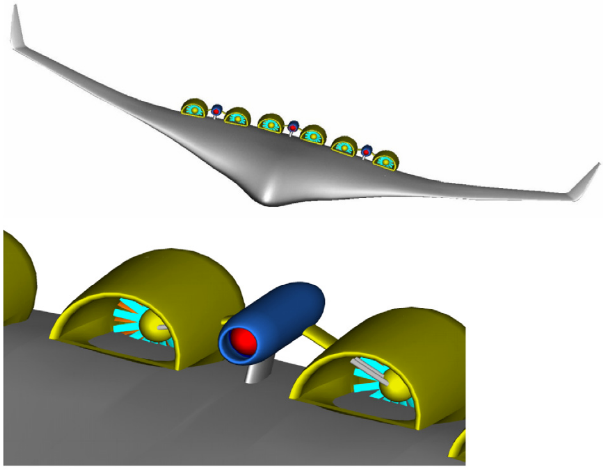

Fig. 7. Hybrid-wing-body (HWB) configuration using gear-driven dual fan with single-engine-core propulsion system [9].

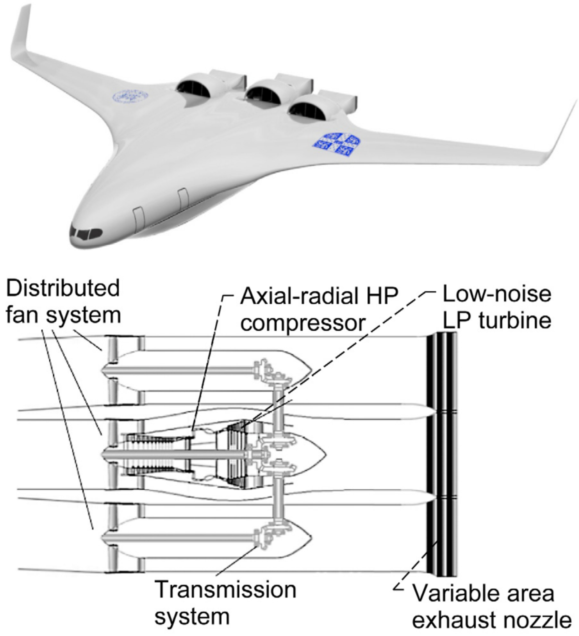

Fig. 8. SAX-40 Silent Aircraft Initiative concept using gear driven three fans with single-engine-core propulsion system [10–12].

2.4.3 Electrically Driven Multi-Fans

To improve performance and to reduce environmental impacts even further, a drastic change in the power transmission of distributed propulsion system for large transport aircraft was proposed and studied on HWB as well as tube and wing airframes [6, 13–19]. Using a new concept called 'turboelectric distributed propulsion (TeDP)', one of the vehicles adopts the previous 12-engine CESTOL-HWB airframe but employs two remotely located gas-turbine-driven superconducting generators to drive the distributed fans instead of using many small conventional engines. The power to drive these electric fans is generated by two remotely located gas-turbine-driven superconducting generators. This arrangement allows the use of many small partially embedded fans while retaining the superior efficiency of large core engines, which are physically separated but connected to the fans through electric power lines. Since this concept is one of the several concepts pursued by NASA to meet N+3 goals, it has become a new area of research at NASA and will be further described in Section 4.

3 Benefits of Distributed Propulsion

As suggested in the above sections, the benefits of using distributed propulsion for aircraft could be found in improvement in aircraft performance, noise reduction to the surrounding community, and/or providing the capability of STOL. Specifically, the following possible benefits of distributed propulsion concepts have been identified through various studies mentioned in previous section:

- Reduction in fuel consumption by ingesting the thick boundary layer flow and filling in the wake generated by the airframe with the distributed engine thrust stream.
- Spanwise high lift via high-aspect-ratio trailing-edge nozzles for vectored thrust providing powered lift, boundary layer control, and/or supercirculation around the wing, all of which enable short take-off capability.
- Better integration of the propulsion system with the airframe for reduction in noise to the surrounding community through airframe shielding.
- Reduction in aircraft propulsion installation weight through inlet/nozzle/wing structure integration.
- Elimination of aircraft control surfaces through differential and vectoring thrust for pitch, roll, and yaw moments.
- High production rates and easy replacement of engines or propulsors that are small and light.
- For the multi-fan/single engine core concept, the propulsion configuration provides a very high bypass ratio enabling low fuel burn, emissions, and noise to surrounding communities.

4 Turboelectric Distributed Propulsion

As seen in Table 1, NASA’s current SFW Project introduces four corners of design trade spaces—in terms of fuel burn, emissions, noise, and field length—to define vehicle concepts for different future time frames, where N+1, N+2, and N+3 represent achieving a TRL of 4 to 6 by the years 2015, 2020, and 2025 respectively. In particular, N+3 vehicle goals are defined as reaching better than 70% fuel burn reduction and better than 75% landing and take-off nitrogen oxides (NOx) reduction, achieving –71dB cumulative below Stage 4 noise regulation, and exploiting metroplex airport operational concepts, compared to current state-of-the-art aircraft. Although it may not be feasible to meet all the goals simultaneously, multi-objective studies are being attempted to identify possible vehicle concepts that have the best potential to meet the combined goals. To meet these aggressive goals, drastic changes in vehicle and propulsion system designs are required and proposed. One of the proposed propulsion systems that may enable meeting the N+3 goals is called “Turboelectric Distributed Propulsion (TeDP)”. The concept employs a number of superconducting electric motors to drive the distributed fans rather than using mechanical shafts and gears. The power to drive these electric fans is generated by remotely located gas-turbine-driven superconducting electric generators. This arrangement enables the use of many small distributed fans, allowing a very high effective bypass ratio (eBPR), while retaining the superior efficiency of large core engines, which are physically separated but connected to the fans through superconducting electric power lines. Although various aircraft configurations using TeDP are possible, three studies have recently been undertaken; their features and important results are presented here.

4.1 N3-X Vehicle Concept by NASA

The HWB vehicle concept using the TeDP was based on the earlier CESTOL airframe configuration shown in Fig. 4 and modified with a new TeDP system [15]. To simplify the propulsion system effects on the vehicle, a more refined conventional take-off and landing (CTOL) ‘N3-X’ vehicle concept shown in Fig. 9 was proposed and is currently being analyzed in greater detail. The airframe is derived from Boeing’s N2A HWB configuration [20] with similar mission characteristics of a 6,000-nmi (11,112-km) range, a 103,000-lb (46,720-kg) payload capacity, and the ability to fly at the aerodynamic design point (ADP) of Mach 0.8 at 31,000 ft (9445 m) altitude. The propulsion system utilizes superconducting electrically driven, distributed low-pressure-ratio (1.35) fans with power provided by two remote superconducting electric generators based on a conventional turbofan core engine design [17]. The use of electrical power transmission allows a high degree of flexibility in positioning the turbogenerators and propulsor modules to best advantage. In the aircraft configuration examined the turbogenerators were located at the wing tips where the turbogenerator would experience undisturbed free-stream conditions, while the fan modules were positioned in a continuous fan nacelle across the rear fuselage where they ingest the thick boundary-layer flow, fill the wake of aircraft with fan discharge air, and thereby reduce the thrust required by the vehicle. The initial result for the propulsion system, using N+2 engine component technologies, consists of two turbogenerators, each producing 53,900 shaft horsepower (SHP) (40.2 MW), and 14 fans of 50.6-in. (128.5-cm) diameter driven by 7,700-SHP (5.74-MW) motors, both at the rolling-take-off (RTO) design condition. The thrust specific fuel consumption (TSFC) is estimated to be 0.2781 at RTO and 0.4685 at the ADP. Table 2 shows the vehicle mission requirements and preliminary engine cycle analysis results using the same vehicle size as the N2A airframe. This study, including vehicle resizing, is ongoing at NASA to obtain more refined data in terms of vehicle fuel burn, emissions, and noise reduction for the mission specified.

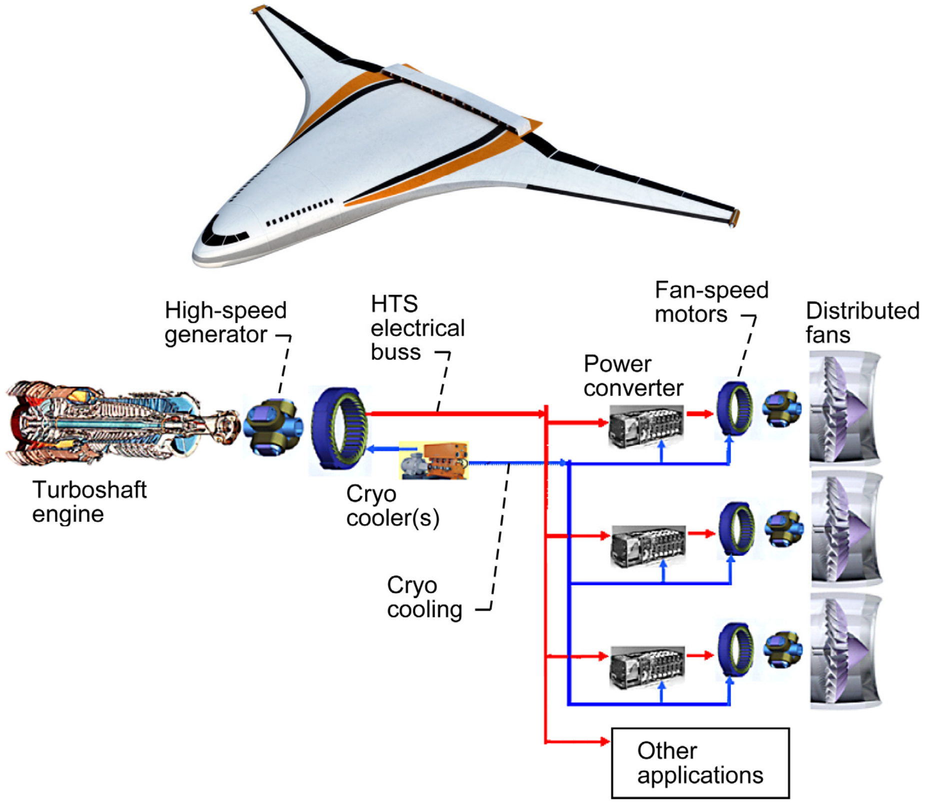

Fig. 9. N3–X vehicle concept using turboelectric distributed propulsion (TeDP) system by NASA [17].

Table 2.—Mission requirements and preliminary engine cycle analysis results of Turboelectric Distributed Propulsion (TeDP) vehicle "N3-X".

Range, nm(km)	6000 (11112)	
Payload, lbf(kg)	103000 (46720)	
Mcruise	0.8	
Cruise Altitude, ft(m)	35000 (10668)	
Number of fans per engine with all engines operating	7	
Fan diamenter, in.(cm)	50.6 (128.5)	
Fan inlet Height, in.(cm)	30.9 (78.5)	
	RTO	ADP
Thrust/engine, lbf (Newton)	54000 (240204)	13950 (62053)
TSFC, lbm/hr/lbf (g/s/N)	0.2781 (7.894)	0.4685 (13.299)
eBPR	20.4	19.2
Generator/engine, SHP(MW)	53,900 (40.2)	26,000 (19.4)
Motor/fan, SHP (MW)	7,700 (5.74)	3714 (2.77)
FPR	1.287	1.35
Fan nozzle exit speed, ft/s (m/s)	751 (228.9)	1003 (305.7)
Turbogenerator OPR	57.08	64.7
Turbogenerator nozzle exit speed, ft/s (m/s)	808 (246.3)	1100 (335.3)

*RTO is rolling take-off; ADP, aerodynamic design point; TSFC; thrust-specific fuel consumption; eBPR, effective bypass ratio; SHP, shaft horsepower; FPR, fan pressure ratio; and OPR, overall pressure ratio.

4.2 "ECO-150/250" Configuration by Empirical Systems Aerospace

As a part of NASA's Small Business Innovative Research (SBIR) phase 1 contract study, Empirical Systems Aerospace, LLC, conducted a system study of integrating an advanced cryogenic electric propulsion system onto a 150-passenger STOL regional airliner, the ECO-150, and a larger 250-passenger large transport, the ECO-250 [18]. A key feature of these two concepts, as shown in Fig. 10, is the integration of the superconducting-electric-motor-driven fans with the wing such that the inboard wing is separated into top and bottom sections, and all electric-driven propulsors are completely embedded within the airfoil or wing structure. This feature provides a benefit of wing weight reduction through wing bending moment relief because the distributed electric fans and the use of the common nacelle as wing rib structure provide stress relief to the wing structure. In addition, a favorable aerodynamic advantage exists such that at low speed, thrust vectoring of a two-dimensional low temperature nozzle may provide supercirculation of airflow around the airfoil for a large improvement in lift coefficient. Another key feature of the concepts is the use of liquid hydrogen both as a cooling fluid for the superconducting system and as fuel for the turboelectric generator engine. Although the study was very preliminary in nature, these propulsion system features along with the vehicle configuration itself did certainly point toward large reduction in fuel burn for both ECO-150 and ECO-250 configurations. The detailed integration and the design of the split wing with electric motors/fans are continuing as a result of another SBIR Phase 1 award.

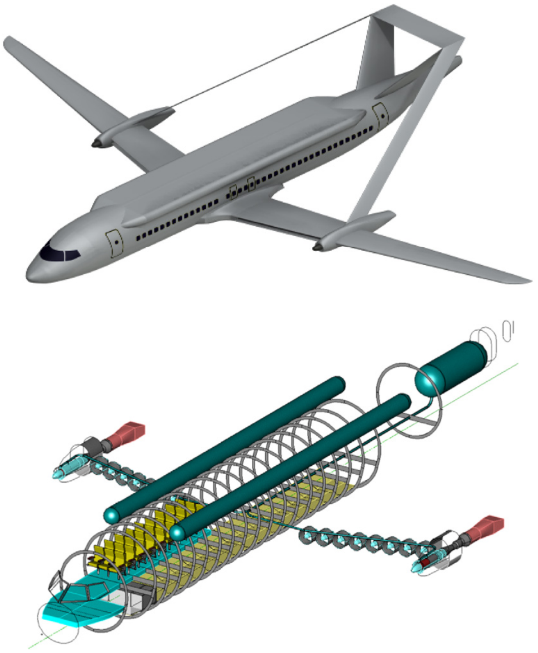

Fig.10. ECO-150 vehicle concept using turbo-electric distributed propulsion (TeDP) system by Empirical Systems Aerospace, LLC [18].

4.3 "H3.1" Configuration by Massachusetts Institute of Technology (MIT)

Another TeDP vehicle concept named "H3.1" was recently proposed and studied by MIT as a part of NASA's SFW N+3 cooperative work [19]. The vehicle shown in Fig. 11 is based on the HWB configuration with a range of 7,600 nmi

Fig. 11. H3.1 vehicle concept using turboelectric distributed propulsion (TeDP) system by Massachusetts Institute of Technology (MIT) [19].

(14,075 km), 354 passengers, and cruise Mach 0.8 at 35,000 ft (10,668 m) altitude. Similar to NASA's N3-X vehicle, this vehicle also ingests upper airframe surface boundary-layer flow to improve propulsive and hence the fuel efficiency while minimizing noise impact to the surrounding community by shielding the propulsion-related noise with the airframe. Another key feature of this configuration is the use of cryogenic methane as fuel because of its higher specific energy, which improve the fuel efficiency of the aircraft. In addition, the cryogenic fuel allows the use of superconducting materials to distribute the electric power from three turboelectric generators to 23 electric fans that are semi-embedded in the upper surface of the airframe.

5 Supersonic Distributed Propulsion Vehicle Concepts

Under the NASA's Revolutionary System Concepts in Aeronautics project in 2004, a system analysis study conducted by the Georgia Institute of Technology examined a 300-passenger supersonic distributed propulsion vehicle. Because this was supersonic flight, an added drag term results from the shock waves surrounding the vehicle. A goal of this study was to minimize this 'wave drag' and possibly reduce the sonic boom on the ground. Depending on the vehicle configuration, this wave drag may constitute from 10% to 50% of the overall vehicle drag. In addition to the wave drag, the shock waves coalesce to varying degrees to cause a sonic boom on the ground. A significant contribution to the shock wave signature is caused by the propulsion pods. By carefully integrating the propulsion pods into the wing structure, a novel configuration might be possible that will reduce wave drag and the intensity of the sonic boom and result in greater overall mission efficiency. Such a notional vehicle concept is shown in Fig. 12.

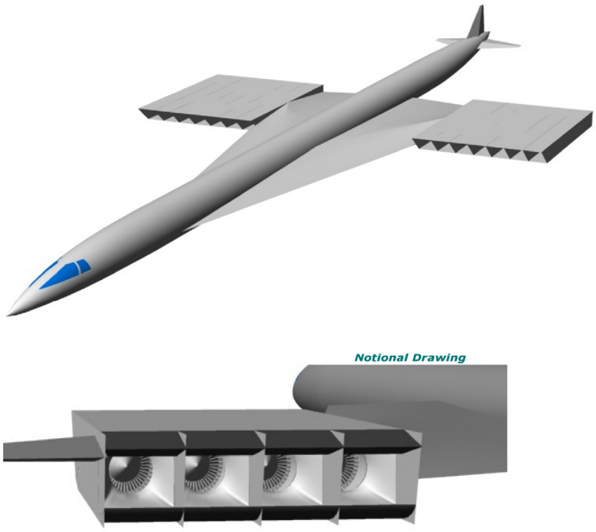

Fig. 12. A supersonic distributed propulsion vehicle concept by Georgia Institute of Technology [20].

6 Concluding Remarks

A main objective of the distributed propulsion concept is to achieve optimum vehicle benefits through integration of aerodynamic, propulsive, structural, and/or operational elements. The concept could be applied to various vehicle configurations such as traditional tube and wing, hybrid-wing-body aircraft (HWB), and supersonic aircraft. However, in order to achieve maximum benefits, it will be necessary to design an aircraft with greater emphasis on propulsion airframe integration right from the conceptual design stage. This paper described some early distributed propulsion vehicle concepts using jet flaps, cross-flow fan, gas-driven multi-fans, or multiple discrete engines. Recent interest in the HWB airframe has prompted other advanced distributed propulsion concepts such as mechanically or electrically driven multi-fans. Among these, the turboelectric distributed propulsion concept seemed to provide a revolutionary capability in terms of fuel burn, emissions, community noise, and field length reductions. The concept uses superconducting turboelectric generators, motors, and transmission lines as a means of transferring power from the turbines to the fans. This power transmission method has the desired effect of allowing the power turbine in the electric generator to spin at any desired speed, while the fans spin at their optimum speed. Not only can the speeds of the turbine and fans be different, but the use of power inverters between the generators and the fan motors allows the speed ratio to change in flight, giving the effect of a variable ratio gearbox. In addition, the use of electrical power transmission allows a high degree of flexibility in positioning the turboelectric generators and fan modules to best advantage. Besides additional modeling and analytical refinement of the electromagnetic, structural, and thermal aspects of the superconducting motors and generators, development of improved subsystems and auxiliary systems is required, such as a lightweight cryogenic systems. With adequate resources and diligent research, superconducting turboelectric distributed propulsion vehicles appear to be a possible and attractive solution for a wide range of configurations and operational possibilities while addressing many current environmental issues.

7 Acknowledgements

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8 Contact Author Email Address

Hyun.D.Kim@nasa.gov

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