Progress in Distributed Electric Propulsion Vehicles and Technologies

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I. Nomenclature

AFRC	=	NASA Armstrong Flight Research Center (Edwards, California)
BLI	=	boundary layer ingestion
BWB	=	blended-wing-body
CESTOL	=	cruise efficient short take-off and landing
C_d	=	drag coefficient
C_l	=	lift coefficient
CTOL	=	conventional take-off and landing
DEP	=	distributed electric propulsion
DOE	=	design of experiment
DP	=	distributed propulsion
EPNdB	=	effective perceived noise in decibels
eBPR	=	effective bypass ratio
eVTOL	=	electric vertical take-off and landing
ESS	=	energy storage systems
f	=	frequency
GRC	=	NASA Glenn Research Center (Cleveland, Ohio)
HE	=	hybrid electric

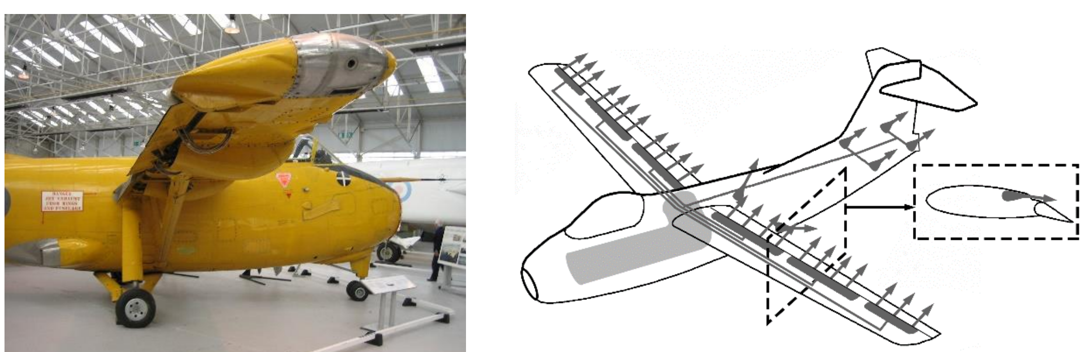
HEIST	=	Hybrid-Electric Integrated Systems Testbed
HWB	=	hybrid-wing-body
NASA	=	National Aeronautics and Space Administration
NEAT	=	NASA Electric Aircraft Testbed
PAI	=	propulsion-airframe integration
PCA	=	propulsion-controlled aircraft
PEGS	=	Propulsion Electric Grid Simulator
STOL	=	short take-off and landing
TeDP	=	turboelectric distributed propulsion
UAV	=	unmanned aerial vehicle
VTOL	=	vertical take-off and landing
α	=	angle of attack

II. Introduction

From the Wright Brothers' Wright Flyer to the British-French supersonic Concorde, civil aviation in the 20th century was rarely marked by disruptive advancement in propulsion technologies. One clear exception to this observation was the development of the jet engine and the resulting derivatives, such as turbofan or turboshaft engines. The continuous, yet incremental performance gains in high-efficiency gas turbine engines over the last eight decades has enabled passengers to travel long distances at high speeds. Modern commercial jet transports are so common that most passengers traveling by air today take the innovative developments of jet engine technologies for granted. However, the ever-increasing demands for travel in the 21st century has also brought an increased awareness of the energy and environmental concerns associated with aviation. Due to the forecasted limited supply of petroleum-based fuel sources and the global warming potential associated with emissions of traditional aircraft propulsion systems, the need for environmentally-responsible solutions in aircraft technology has been recognized as a priority in the development of future aircraft configurations. In order to address these concerns, future aircraft concepts must be developed to reduce energy usage, community noise, and emissions associated with passenger- or cargo-carrying aircraft [1]. One of the proposed propulsion concepts that seeks to meet these aggressive objectives is defined as distributed electric propulsion (DEP) and is being studied across various government, industry, and academic organizations. This chapter provides an overview of various aspects of the DEP concept, including electric component level technology developments, newly developed aircraft configurations, and merits and challenges that are uniquely associated with the DEP concept.

In order to describe the DEP concept, a more general concept called distributed propulsion (DP) is first explained. Within the context of an air transportation system, a simple definition of DP can be described as a propulsion system where the vehicle thrust is produced by one or more propulsors that are distributed across the air vehicle. Although a formal definition of a DP system has not yet been established, in general, the distributed thrust capabilities of a DP system should serve an enabling role in improving the system-level efficiency, capabilities, or performance of the air vehicle. Regardless of its definition, DP for air vehicles has generally been applied through one of the following:

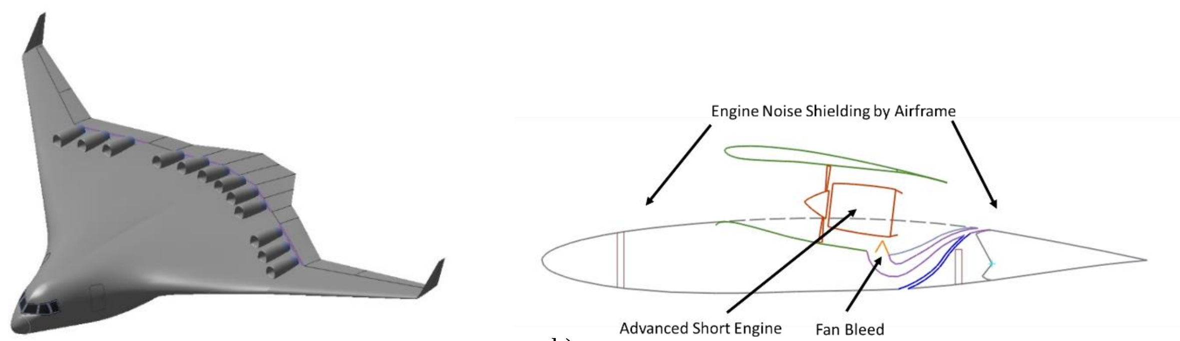
- Jet flap or distributed jet – A concept where a high-velocity, thin jet sheet emanates from a tangential slot at or near the wing trailing edge and provides spanwise thrust for high lift or cruise applications.
    - An example of a jet flap system can be found in the Hunting (now BAE Systems, London, United Kingdom) H.127 aircraft, as shown in Fig. 1, and an example of a distributed jet can be found in the propulsion system for a stealth fighter F-117 aircraft (Lockheed Martin, Bethesda, Maryland) or the Ball-Bartoe Jetwing (Ball-Bartoe Aircraft Corporation, Boulder, Colorado).



a) b)

Fig. 1. Hunting H.127 aircraft: a) photograph of jet flap system, used with permission from Mark Murphy under CC BAY-SA 3.0 license, b) schematic of jet pneumatic distribution system.

- Multiple independently powered propulsors – A distribution of the vehicle thrust stream across an array of independently operated propulsors, which are integrated across the aircraft to produce a beneficial coupling in the aircraft system-level performance.
    - Any aircraft with more than one propulsor may technically be viewed as having a thrust stream distributed across the platform. However, a DP concept of this class typically features an array of independently powered engines or propulsors are synergistically coupled into the airframe, such that the propulsive units serve an integral role in enabling enhancements in the vehicle flight efficiency, high-lift capabilities, maneuverability, or other performance characteristics. An example is NASA's Cruise Efficient Short Take-Off and Landing (CESTOL) configuration, shown in Fig. 2, where 12 small conventional engines are distributed on the upper surface of a hybrid-wing-body (HWB) airframe to enable short take-off and landing (STOL) performance [2].

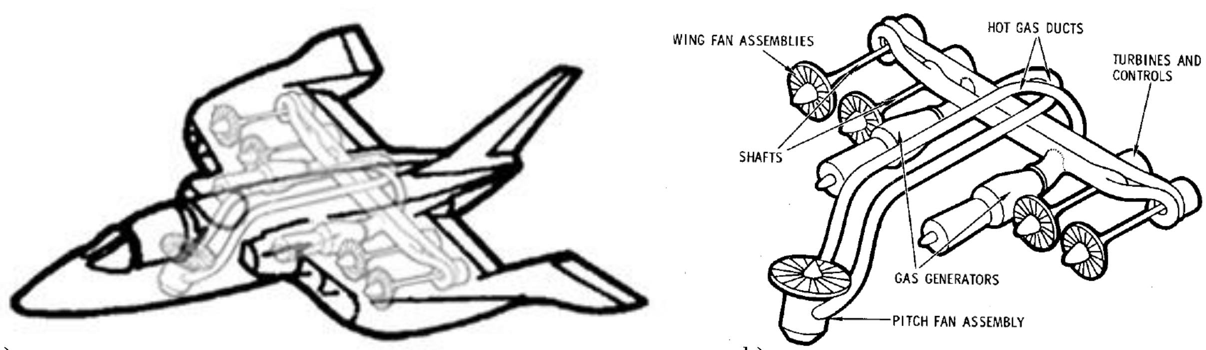


a) b)

Fig. 2. NASA CESTOL aircraft with embedded engine system: a) isometric view of CESTOL aircraft concept, b) cut-away schematic of embedded engine system.

- Distributed propulsors driven by one or more power sources through various power transmission methods – Under this category, the classification of a DP system does not rely specifically on the placement location of propulsors, but rather the power transfer approach from the power sources to propulsors utilized by the aircraft. Conventionally, three types of power distribution approaches for propulsion have been generally utilized in a DP system.

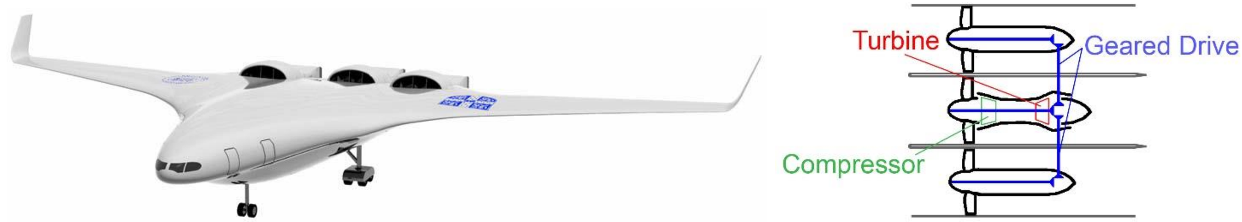
- The first type of system is designed with multiple propulsors powered by fluidic energy provided from separately-located power sources. An early example of this type is the ADAM III concept [3] where the "hot" core exhaust air of two gas generators was redirected to drive a series of propulsive fans embedded within the wings and the fuselage of the aircraft. An example schematic of this drive system is shown in Fig. 3. Another example of this type is a concept [4] where the relatively "cold" source of compressed air is discharged from the compressor stage and routed to power multiple tip-driven propulsors.



a) b)

Fig. 3. ADAM III concept aircraft, a) isometric view of strike-reconnaissance concept aircraft, b) gas duct system, from "ADAM III V/STOL Concept" by Winborn, B.R. [3]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

- The second type is a system where power is provided to multiple propulsors by one or more mechanical transmission methods. An early example of this type is the Wright Flyer, where a single power plant was used to provide mechanical power to two propellers via a series of interlinked chains. Some recent examples of this type include NASA's dual-fan on the blended-wing-body (BWB) concept where the propulsion system consists of an engine core with two mechanically connected ducted fans through gears and shafts [5]. Another concept of this type is the SAX-40 configuration by the Silent Aircraft Initiative [6-9] where the engine provides similar mechanical power to three separate fans, as shown in Fig. 4.



a) b)

Fig. 4. SAX-40 concept aircraft, a) isometric view from Liu [9], reprinted by permission of the Cambridge University Press; b) sketch of geared drive system for ducted fans.

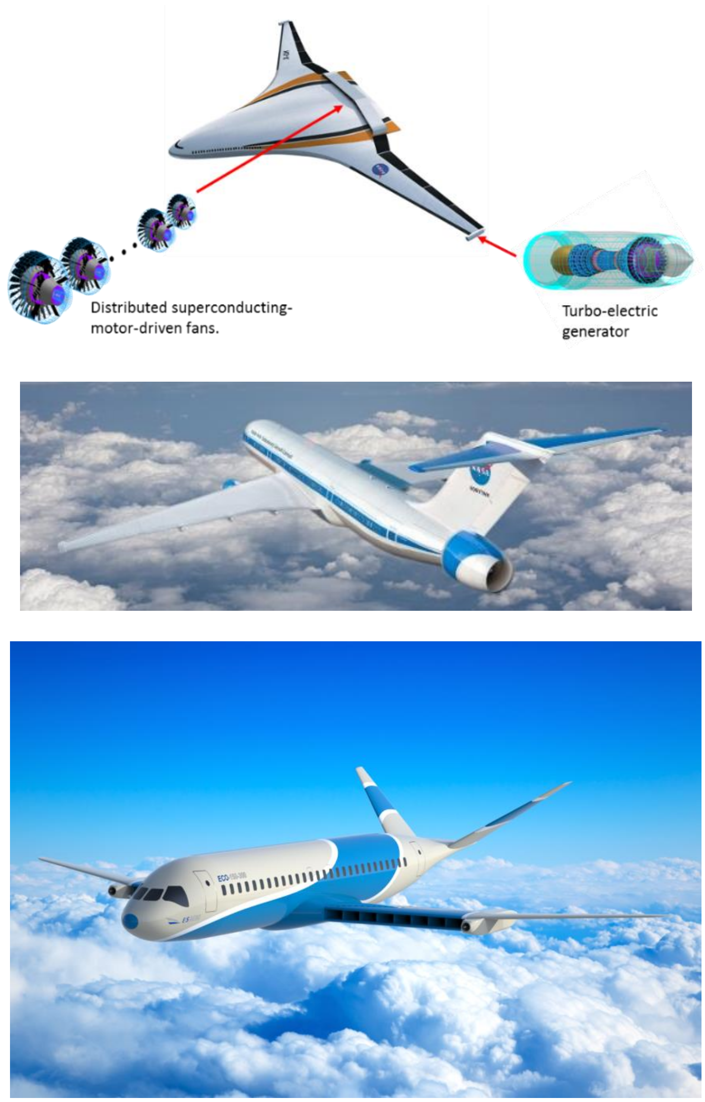
- The third type is a system where electrical energy sources are connected, via transmission lines, to multiple electric motor-driven propulsors. Since this type of propulsion system, now called "distributed electric propulsion (DEP)," is the main focus of this chapter; further description of this particular type of propulsion system is presented in the remaining sections.

III. Distributed Electric Propulsion Technologies and Aircraft Concepts

When considering the multiple electric motor-driven propulsors of a DEP system, the traditional word "engines" related to an aircraft power plant is intentionally not used to avoid confusion between the power sources of the aircraft and the propulsors. For example, on a DEP system the thrust-producing propulsors do not share a common mechanical power transmission system with the power-producing components of the system. Instead, the power sources can be any combination of electrical power-producing devices (that is, electric generator, fuel cell, et cetera) and energy storage devices (that is, battery, capacitor, et cetera), while the propulsors can be any combination of thrust producing devices such as electrically-driven propellers or fans of various sizes and types. Due to this decoupled feature between the power sources and propulsive devices, many different revolutionary aircraft configurations are now possible if highly-efficient, compact electric machines and transmission systems are employed.

In recent years the increased popularity of the DEP concept and the rapid maturation of electric systems for aircraft applications have enabled a variety of new technologies and aircraft configurations. Based on currently-available and near-term electrical components and subsystems, there are now a number of DEP-enabled aircraft concepts that are configured and even demonstrated in flight by various organizations throughout the world. However, due to the limited specific power or specific energy of currently-available electric hardware, practical development of early DEP concepts have been limited to small aircraft configurations that are unmanned or carry only a few passengers. With the persistent interest of improving efficiency, decreasing operating costs, and encouraging environmental responsibility of larger commercial aircraft applications, there are now organizations investing in and researching DEP systems for larger passenger and cargo-carrying capabilities.

One subset of the DEP concept is called turboelectric distributed propulsion (TeDP), which was initially suggested by NASA [10] and is currently being studied across various research and industry organizations. The TeDP concept employs a number of highly-efficient, light-weight electric motors to drive a number of distributed electric propulsors. The electric power to drive these propulsors is generated by separately-located electric generators, which are driven by one or more gas turbines. This arrangement enables the use of many small distributed electric propulsors, allowing for a very high effective bypass ratio (eBPR) while retaining the superior efficiency of large engine cores that are physically separated from the propulsors. The electrical power transmission method has the desired effect of allowing the combined gas turbine and electric generator to be operated at any desired output level, while the propulsors can be operated at separate, optimum rotational speeds. Not only can the operating levels of the turbine and propulsors be different, but the use of power inverters between the generators and the propulsor motors allows the operating ratio to change in-flight, giving the effect of a variable-ratio gearbox. In addition, the use of electrical power transmission allows for a high degree of flexibility when positioning turboelectric generators and propulsor modules to best take advantage of synergistic propulsion-airframe integration (PAI) benefits. The TeDP concept also resolves current limitations in specific energy of electrical energy storage for large aircraft platforms, as traditional aviation fuels can instead be used as an energy carrier and converted to electrical power in-flight. Some aircraft concepts, including the NASA's N3-X [11-13] and the Single-Aisle Turboelectric Commercial Transport with Fuselage Boundary Layer Ingestion (STARC-ABL) configurations, as well as the Empirical Systems Aerospace (ESAero) ECO-150 concept employ such a propulsion system shown in Fig. 5.



a) b) c)

Fig. 5. Commercial transport-class TeDP aircraft concepts: a) NASA N3-X, b) NASA STARC-ABL, and c) ESAero ECO-150, image used with permission from Empirical Systems Aerospace, San Luis Obispo, California.

The turboelectric N3-X aircraft, shown in Fig. 5(a), is designed with an array of 14 electrically-powered ducted fans, which are integrated into the upper-surface trailing edge of the aircraft center-body region. The electrical power is produced by two turboelectric generators which are located at the wingtips. Additionally, the N3-X aircraft utilizes a superconducting electrical transmission system which allows the aircraft to obtain at least 60-percent reduction in energy consumption as compared to the best in class current generation transport aircraft [12]. A recent, but simplified TeDP aircraft configuration called the STARC-ABL concept is actively being studied by NASA [14, 15]. As shown in Fig. 5(b), this concept features a conventional tube-and-wing architecture with two underwing turbofan engines with electric generators that extract power from the engines and transfer it to a fuselage-mounted boundary-layer ingestion (BLI) electric fan at the aft end of the aircraft. Variations of the turboelectric ECO-150 concept, shown in Fig. 5(c), exist for both civilian transport and military applications. The ECO-150-16 airliner variant is designed with one turboelectric generator near the mid-span of each wing and eight electric ducted fans placed in a “split-wing” configuration between the upper and lower surfaces of inboard wing section [16, 17].

In addition to TeDP propulsion systems, other DEP systems are also being proposed and developed for conventional takeoff and landing (CTOL), short takeoff and landing (STOL), or vertical take-off and landing (VTOL) aircraft applications. For the smaller regional aircraft market, Zunum Aero has been working on a family of 6 to 50 passenger hybrid-electric (HE) propulsion aircraft [18]. Two variants of the Zunum regional aircraft concept are shown in Fig. 6(a), for 10-seat and 48-seat configurations, each with two fuselage-mounted electric fans powered by a combined system of a turboelectric generator and batteries. This type of HE propulsion system on a small conventional aircraft enables a high-efficiency drivetrain with reduced energy consumption and low-cost operation, as compared to similarly-sized conventional aircraft. Similarly, Eviation’s Alice Commuter aircraft, shown in Fig. 6(b), was designed to carry up to 9 passengers across regional transportation and commuting markets. Unlike other regional transport concepts, the Alice was designed with a fully-electric propulsion system, using three electrically-driven propellers. The main pusher propeller used for this concept is embedded into the tail of the aircraft, with two additional propellers located on the wingtips. Placement of the propellers in these locations was performed to produce beneficial aero-propulsive coupling effects, which will be further described in Section VI.


a)


b)

Fig. 6. Regional and commuter aircraft, a) family of Zunum Aero concepts, used with permission by Zunum Aero, Bothell, Washington, and b) Eviation Alice Commuter aircraft, used with permission by Eviation Aircraft, Israel.

A series of smaller aircraft systems intended for 3-6 passengers have also been developed, as shown in Fig. 7, where the DEP system is incorporated into the airframe to augment high-lift capabilities at takeoff and landing. An example is the NASA X-57 Maxwell demonstrator aircraft [19,20] shown in Fig. 7(a). This aircraft is based on a Tecnam (Casoria, Italy) P2006T aircraft that has been reconfigured with a new wing, having a much shorter chord and higher aspect ratio than the baseline Tecnam aircraft wing. This all-electric aircraft is powered solely through a series of battery packs. The reduced wing area associated with this design is achievable due to the high lift on the wing enabled with the use of 12 small electrically-driven propellers along the leading edge of the wing, which are operated during the takeoff and landing phases of flight. The primary purpose of these 12 distributed propellers is to produce a blown wing effect, where an increase in the effective dynamic pressure over the wing at low speed results in an increase in the lift produced, as compared to an unblown wing surfaces [20]. During the cruise segment of the flight, two wing-tip mounted large electric propellers are the main propulsors which enable up to 5 times reduction in energy usage compared to the original two propellers of the P2006T aircraft, while the 12 smaller inactive propellers at the leading edge of the wings are folded into each nacelle. Another DEP-enabled aircraft called the AMPERE is a 4 to 6 passenger general aviation STOL aircraft concept under development by ONERA (Palaiseau, France) [21]. The AMPERE concept shown in Fig. 7(b) features an array of 40 small ducted electric fans mounted at the leading edge of the upper surface of the wing to provide an upper surface blowing effect to increase the lift at low speed. The power delivered to these fans are provided by a combination of batteries and hydrogen fuel cells.

a) b)

Fig. 7. Aircraft with high-lift DEP systems including, a) NASA all-electric X-57 Maxwell and b) ONERA AMPERE aircraft concept, used with permission by ONERA, Palaiseau, France.

Expanding on the concepts of DEP-enabled CTOL and STOL aircraft, the electric vertical take-off and landing (eVTOL) aircraft market has also recently emerged, which has been guided by the growing Urban Air Mobility (UAM) movement. The concept of UAM is motivated not only by the need to relieve ground traffic congestion in highly-populated areas, but also to provide “on-demand” air service as suggested by the ride-sharing company, Uber

Technologies Incorporated (San Francisco, California) [22]. This aspiration has led to a unique set of design constraints which can be met by current or near-future technology levels of electric drivetrain components, due to the limited range requirements of short-haul aerial vehicles. A variety of companies, such as Airbus and Uber, have invested heavily in developing vehicles to provide aerial taxi services in crowded urban environments. Examples of battery-powered eVTOL aircraft concepts include the Joby Aviation (Santa Cruz, California) S2 aircraft, the Lilium (Munich, Germany) jet, and the Airbus (Leiden, Netherlands) Vahana aircraft concept. Additional concepts include the eHang184 (EHANG, Guangzhou, China), the Volocopter 2X (Volocopter, Bruchsal, Germany), and the Aurora Flight Sciences (Manassas, Virginia) PAV. Several of these example eVTOL aircraft are shown in Fig. 8, and described in the following paragraphs.

a)

b)

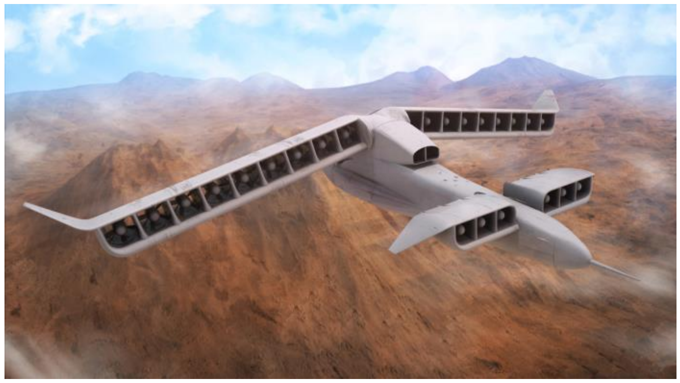
c)

Fig. 8. Example DEP eVTOL passenger aircraft configurations including, a) Airbus Vahana VTOL aircraft, used with permission by Airbus, Leiden, Netherlands, b) Lilium jet, used with permission by Lilium, Munich, Germany, and c) Joby S2 aircraft, used with permission by Joby Aviation, Santa Cruz, California.

The desire for eVTOL capabilities coupled with improved cruise efficiency over conventional multi-rotor configurations has also led to the development of several DEP tiltwing aircraft designs such as the Airbus Vahana concept [23], shown in Fig. 8(a). In these concepts, propulsors are mounted on the wing, which rotates to a vertical direction for VTOL operation and transitions during flight to a horizontal direction for cruise operation. The Lilium Jet, shown in Fig. 8(b) is a different take. Similar to the Airbus Vahana, it is powered by batteries only, and is designed for aerial taxi services [24]. For this aircraft, the ducted fans are mounted to the wing and canard upper surfaces across an array of trailing-edge flaps. These fans are configured in clusters of three fans per flap segment. The attitude control and the transition between vertical and horizontal flight is performed through the rotation of the flap surfaces of the wing and canard. In comparison to a CTOL configuration, the Lilium Jet is unique in that it does not have a traditional vertical surface to provide yaw stability. Instead, yaw control is produced by introducing asymmetric thrust through the DEP system. The Joby S2 aircraft, shown in Fig. 8(c) is another example of a small-winged aircraft with eVTOL capabilities which has been outfitted with leading-edge foldable propellers on both the wing and v-tail [25].

The eHang184 [26] and Volocopter 2X [27] configurations are both multicopter designs, where the eHang184 is configured with 8 rotors and the Volocopter 2X with 18. These configurations can be considered as an extension of the multi-rotor Unmanned Aerial Vehicle (UAV) approach to vertical flight, where the use of multiple smaller rotors enable the use of efficient, light-weight electric motor systems. An additional feature of these configurations is that they are completely battery powered, which makes their operation cost-efficient for short-range commutes within a crowded city due to the relatively inexpensive electric energy cost compared to traditional aviation fuel. Unlike these two configurations, Aurora's PAV [28] uses eight small vertically-mounted rotors for VTOL operation and a large propeller behind its fuselage for forward thrust. This approach utilized by Aurora's concept permits the use of fixed wings during cruise, as well as faster forward flight speeds.

The XV-24 LightningStrike and NASA GL-10 UAV, shown in Fig. 9, also fall into the category of eVTOL DEP aircraft, although their application is not geared toward personal transportation. In the Aurora Flight Sciences XV-24 eVTOL configuration, shown in Fig. 9(a), a turboelectric generator provides power to multiple electric fans that are completely embedded in the wing, providing not only VTOL capability, but also high speed cruise capability. This concept features a total of 24 ducted fans located between the upper and lower surfaces of the wings and canard. The LightningStrike was under development as an X-Plane by the Defense Advanced Research Projects Agency (DARPA), and was designed to provide unmanned military support with VTOL and high cruise speed capabilities [29]. The GL-10 aircraft, shown in Fig. 9(b), is another DEP configuration developed by NASA. This aircraft is outfitted with 10 propellers, 8 of which are located across the leading edge of a tilting wing and two on the horizontal stabilizer. Work has been performed to demonstrate how a flight controller can be developed for a complicated system with a total of 21 control actuators and applicability to hover, transition, and forward flight modes [30].

a) 

b) 

Fig. 9. Example DEP eVTOL UAV configurations including, a) Aurora Flight Sciences turboelectric XV-24A LightningStrike aircraft, image used with permission by Aurora Flight Sciences, Manassas, Virginia, and b) NASA GL-10 UAV.

With respect to DEP-enabled vehicle capabilities and subsystem improvements, other subject areas are highlighted and discussed further in the subsequent sections. These technical subject areas include: 1) highly efficient, light-weight electric motors, generators, inverters, and associated electric transmissions systems; 2) electric grid simulation systems for DEP vehicles, 3) PAI benefits realized through innovative vehicle system concepts; 4) aerodynamic and propulsive thrust coupling effects; 5) vehicle control, noise reduction, and airframe structural tailoring. Furthermore, while the advancement of DEP concepts and associated technologies have seen relatively rapid developmental progress during the last decade, some of the current barriers, challenges, and developmental needs for DEP systems are also presented and discussed.

IV. Electric Component Research and Development

Given the use of electrically-driven propulsors for DEP aircraft, extensive development in all areas of energy storage systems (ESS), electrical power transmission and handling, and control is currently being conducted in order to provide increased feasibility and efficiency of such systems. While current capability levels are sufficient for DEP systems to be integrated into small UAVs and certain classes of general aviation vehicles, additional improvement in component technologies is necessary before flight-weight, high-power machines and power electronics are appropriately sized for larger classes of aircraft, such as regional and commercial transport applications. However, when used in a DEP architecture, the rated power requirements required for individual electric machines and power electronics components can be expected to be markedly lower than those required for direct electrified replacements of isolated propulsors used on traditional aircraft configurations. This lower power requirement comes from the ability to leverage an array of electrically-driven propulsors to provide an equivalent thrust or propulsive power capability of one jet engine, making DEP architectures accessible earlier than direct hybrid-electric or all-electric replacements of isolated propulsion systems.

Current research in permanent magnet [31, 32], induction [33], and wound field [34] electric machines are now producing concepts able to reach megawatt power scales, with specific power values of 13-16 kW/kg. An image of a flight-weight 1 MW permanent magnet motor being developed at the University of Illinois at Urbana-Champaign is shown in Fig. 10. The use of carbon nanotube conductors for motor electric coils is also an area of exploration, which would lead to as much as an 84-percent reduction in motor coil weight for a fixed power capability, as compared to those produced with copper conductors [35]. An example of the formation of carbon nanotube fibers is shown in Fig. 11, after Tsentalovich et al.[36] Similarly, the introduction of wide-bandgap (WBG) semiconductors have led to new capabilities of power electronics, such as those utilized on naval ship systems [37]. These WBG components offer several advantages over traditional Silicone (Si) devices. Notable WBG devices include Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect-Transistors (MOSFETs), and Gallium Nitride (GaN) transistors, both of which feature lower switching losses, faster switching speeds, and higher melting points than traditional Si counterparts [38]. In addition to using new materials, new switching topologies for inverters are also being studied [39]. These developments in power electronics have produced converter concepts with power ratings up to 1 MW at a specific power of 12 kW/kg and 99-percent efficiency [40]. Other converter concepts feature, liquid- or cryogenically-cooled variants with an intended specific power range of 19-26 kW/kg. [34].

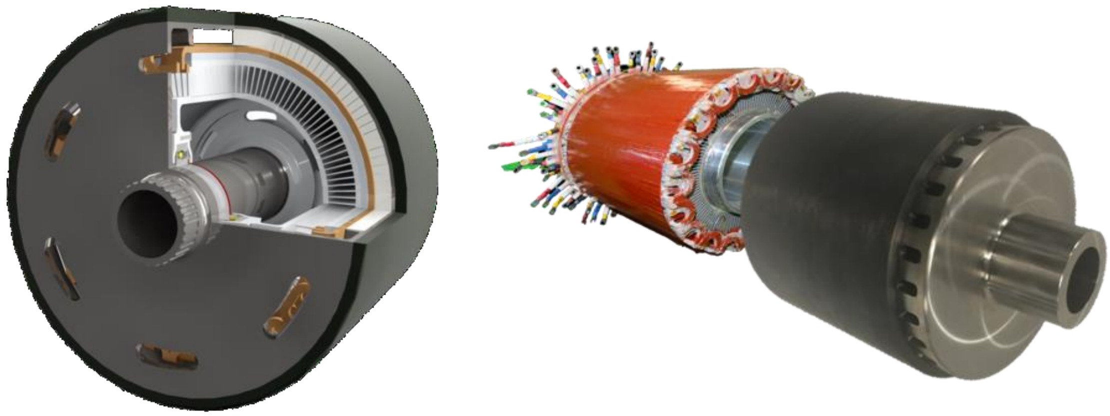


Fig. 10. 1 MW permanent magnet electric motor [31], used with permission by the University of Illinois at Urbana-Champaign, Urbana, Illinois.

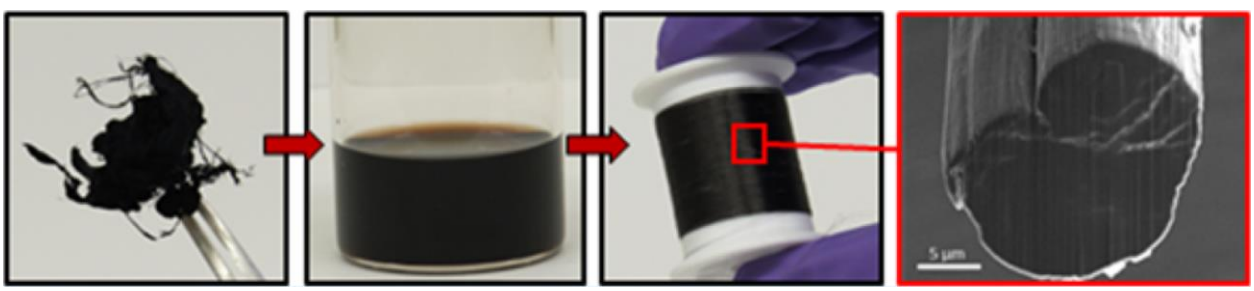


Fig. 11. Development process of carbon nanotube filaments, adapted with permission from Tsentalovich et al [36]. Copyright 2017 American Chemical Society.

Operational voltages of power transmission systems are also currently limited to 540 V, based on common conductor insulation and termination practices, to prevent breakdown and partial discharge at flight altitudes via Paschen's law [41, 42]. This transmission voltage limit can be increased with the use of pressurization systems and novel insulation materials. Previous studies have revealed an optimum power distribution voltage on a large DEP vehicle to fall within a range of 8-10 kV (±4 to ±5 kV) for system architectures that rely on breakers for circuit protection, or 4 kV (±2 kV) for systems that utilize converters for isolation and redundancy [43, 44]. Despite the lower specific power of cryogenic machines, many studies involving DEP systems have turned to cryogenic systems in design trade studies [11, 12, 44, 45], though not all [14, 35, 46]. Additionally, given that the total length of conductors required for power transmission is expected to scale relative to the number of propulsors on a DEP aircraft architecture, it is highly desirable to increase the transmission voltage above present limitations to reduce overall transmission losses across the aircraft drivetrain. Doing so would produce a lower current-carrying requirement of small and light conductors, while also reducing resistive losses. However, it has also been identified that for large DEP aircraft, cable system weights and efficiencies are effectively negligible in comparison to the rest of the aircraft platform [43].

In order to coordinate power distribution throughout a DEP system, various architectures and methods for control have been studied. Considering factors such as weight, robustness to failures, bus distribution flexibility, complexity, and excess power capabilities can lead to drastically different power distribution architectures for the same vehicle-level requirements. While reducing the complexity of power distribution systems can be desirable, use of simple architectures often requires oversized components to ensure fault tolerance on the vehicle system level. By providing flexibility in the power distribution architecture to prevent oversizing of propulsors, Armstrong et al. [47] were able to reduce propulsor weights by 42-percent relative to a baseline configuration. Various approaches to regulating the flow of power across fixed architectures include the application of a simple rule-based control, fuzzy logic control, and neural network control [48]. An example of these power system architectural trade-offs applied to an aircraft system can be found in a study performed by Loder et al. [49]. In the study, three power distribution architectures were proposed for use on the ECO-150 and compared against each other in terms of efficiency and weight, based on sizing estimates of current and near-future state-of-the-art electrical components. The architectures included an AC synchronous distribution, a DC distribution, and a hybrid AC/DC distribution. Key conclusions from this study point to a tradeoff between efficiency and weight when selecting between an AC or DC power distribution architecture with AC being the most efficient and a high-voltage DC providing the lowest weight option. Hybrid options were observed to be prohibitive in terms of weight and/or efficiency. Given that no power distribution architecture is universally optimum for all DEP aircraft configurations, tradeoffs must be assessed at the aircraft system level, with each configuration featuring a unique set of electrical design challenges.

Ensuring circuit protection and fault tolerance across the aircraft power system is also crucial in a DEP aircraft configuration for safety considerations. While often overlooked, improvements are being made in circuit breaker technologies for system protection with high-power, lightweight capabilities. Traditional mechanical circuit breakers have been deemed to be too large and have too long of a response time to be feasible for DEP applications [35]. Instead, solid-state [50, 51] and hybrid mechanical/solid-state [52] circuit breakers have been proposed for use in DEP power architectures, along with reactors and superconducting fault current limiters [47]. Previous work has also identified the key electrical components and constraints which are required for an electrically-powered DP aircraft [53]. In the study, a survey of currently-available breakers, converters, and fault-current limiters was conducted, and fault-management architectures from other industries were evaluated along with current and predicted technological readiness levels to guide the design of fault-tolerant electrical propulsion systems. A need for further development of the electrical components which enable a fault-tolerant system was identified as a main conclusion to this study.

One additional benefit to DEP-enabled aircraft configurations is the increased level of fault tolerance which is provided under failures of individual propulsor or electric power source units, as compared to traditional propulsion schemes. The power sources can be a combination of multiple turboelectric generators, battery systems, fuel cells, or other devices. This fault tolerance is produced across two levels. First, structural damage to the airframe or the loss of traditional control surfaces are less detrimental to aircraft survivability when a DEP system is used, as propulsors can be used to generate forces and moments about all six degrees of freedom of the aircraft. In such instances, the propulsion system can be used for control, as discussed in Section VII. This methodology has been demonstrated on small-scale UAVs with an adaptive control law which allowed the aircraft to remain in controlled flight after all control surfaces were intentionally disabled [54]. Second, there is decreased criticality associated with the loss of a small number of propulsion units, including both propulsors and power sources, as the total thrust required can be re-distributed accordingly [55].

V. Distributed Electric Propulsion Component Integration and Grid Simulation Systems

The technologies that will enable efficient and safe operation of DEP systems include highly-efficient, light-weight, flight-quality electric subsystem components such as motors, generators, inverters, controllers, transmission systems, and ESS. In a DEP system, these components are assembled together and installed across an airframe to provide an improved propulsion system. Previous studies have provided insights into the distribution of electric power and energy across a range of platforms, from small-scale to large transport-class aircraft. In addition, a series of dynamic simulations of DEP systems were conducted to design and characterize these systems, which have informed detailed trade studies of system architectures, required components, operating conditions, and fault scenarios [43, 44, 56-58]. To provide a validation platform for candidate electric systems, a subscale desktop experimental testbed called the Propulsion Electric Grid Simulator (PEGS) was developed at the NASA Glenn Research Center (GRC) in

Cleveland, Ohio to emulate an entire TeDP power system, from the turbine engines to the distribution of electrically-driven propulsors [59, 60]. An image of the PEGS system is shown in Fig. 12.

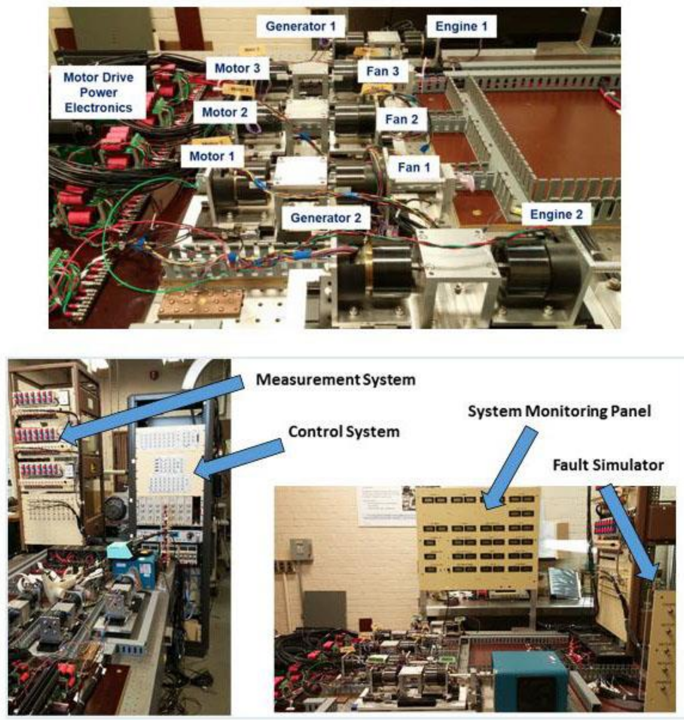


Fig. 12. PEGS subscale electric power system for TeDP [60].

For a 200-kW capable system, the Hybrid-Electric Integrated Systems Testbed (HEIST) was utilized at the NASA Armstrong Flight Research Center (AFRC) in Edwards, California to study power management and flight control laws to enable hybrid-electric DEP hardware integration and piloted simulations [61]. An artist's rendition of the HEIST test platform is shown in Fig. 13. The testbed has a 31-foot-span wing with 18 high-performance electrically-driven propellers, motors, controllers, a battery system, a turboelectric generator, dynamometers, and supporting power communication infrastructure that are all connected to the AFRC Core Simulation [62] for design and flight performance evaluation. In order to provide a full-scale large electric aircraft powertrain test capability with a reconfigurable electrical system architecture, the NASA Electric Aircraft Testbed (NEAT) has also been developed at NASA GRC. A schematic of the NEAT platform is shown in Fig. 14. For testing of the electrical powertrain only, the NEAT supports a system configuration up to the scale of a large single-aisle commercial aircraft and can handle up to 24 MW. The motors and generators are configured to match the speed, torque, and inertial characteristics of turbines and distributed fans at all segments of an airplane mission. In addition to the above NASA testbed development efforts, there have been a number of industry efforts addressing electric architectures of DEP systems. For the TeDP system in particular, a paper by Armstrong et al. presented various options for electric system architectures, voltages, and components required for large transport aircraft [43].

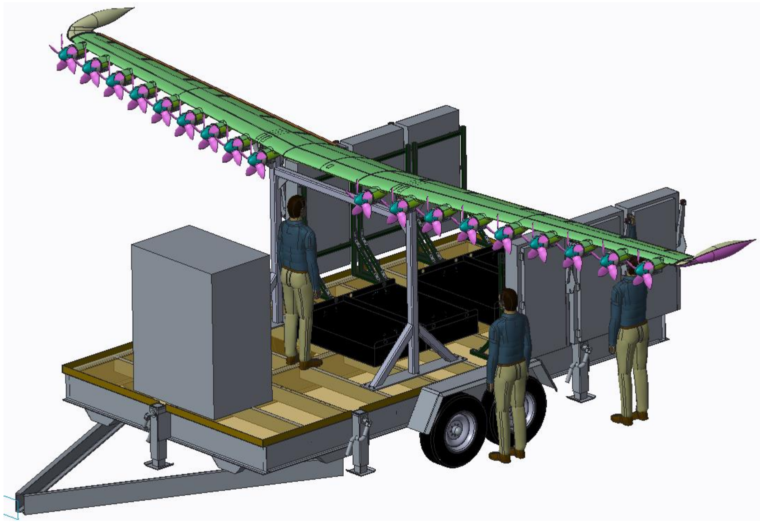


Fig. 13. HEIST testbed at NASA AFRC.

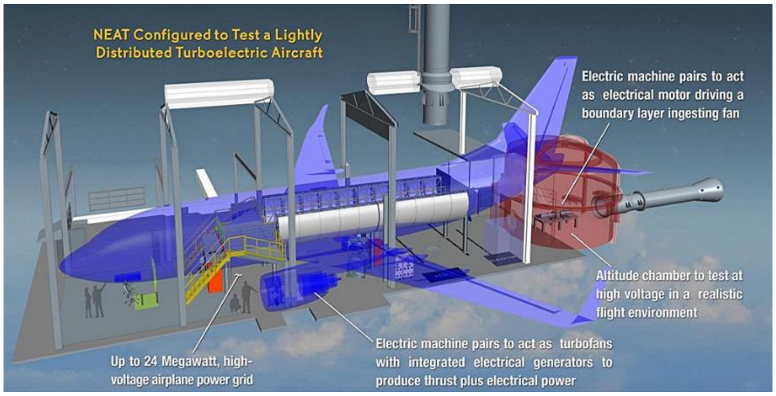


Fig. 14. NEAT platform for full-scale turboelectric powertrain testing at NASA GRC.

VI. Distributed Electric Propulsion Enabled Aero-Propulsive Coupling

One of the inherent features of a DEP-enabled aircraft described in Section II is the synergistic integration of the propulsion system into the airframe of the aircraft [63]. Given this close integration of the distributed propulsion system and aerodynamic surfaces, a series of complex system interactions are often produced due to the resulting aero-propulsive coupling effects which depends largely on the type of propulsion unit in use (for example, propeller versus ducted fan) and the proximity of those propulsion units to the wings, tail surfaces, or fuselage. One significant advantage of synergistically integrating a DEP system on an airframe is that with innovative design, the propulsion-airframe integration (PAI) can be used advantageously. The benefits of aero-propulsive coupling can be broadly attributed to several categories:

1) Improved propulsive efficiency: By ingesting the low-momentum airframe boundary layer flow across a propulsor inlet streamtube, the propulsive efficiency can be increased above those produced by the same propulsor with a boundary layer diverter [64]. This effect can be explained by the reduced kinetic energy increase required across the propulsor to produce a required thrust when the inlet velocity is decreased.
2) Vehicle drag reduction: The strategic placement of propulsors can reduce the drag of an aircraft through a variety of mechanisms, including the use of the swirling flow induced by a propulsor to actively suppress circulation shed into a wing trailing vortex system, resulting in reduced induced drag.
3) Enhanced lift or control authority: The interaction of a propeller or fan slipstream with an aerodynamic surface can be used to provide increases in local dynamic pressure beyond that of the freestream, which acts to augment aerodynamic loading across these regions. Furthermore, the pressure and velocity variations produced across a propulsor streamtube can act to change several key flow characteristics that govern the aerodynamic performance of a wing section, such as the enhanced lift through additional circulation effects or boundary layer flow control.

Each of these categories of aero-propulsive coupling, which occur on a variety of distributed propulsion aircraft configurations, are discussed in the next paragraphs.

To date, BLI has been the most investigated of the aero-propulsive coupling effect associated with a distributed propulsion system. The primary benefit associated with BLI is the potential for reduction in energy usage due to ingestion of the thin, low-momentum flow caused by friction between the inviscid flow and the aircraft surface. This technology results in an increase in propulsive efficiency, and it can also be used to reduce turbulent mixing losses manifested in an aircraft wake by directly re-energizing viscous velocity deficits produced by the vehicle [65, 66]. Many of the previously-mentioned DEP vehicles were designed to take advantage of BLI. First among these is the N3-X aircraft, where the embedded DEP system across the downstream portion of the HWB upper surface was shown to produce benefits when configured to ingest the large boundary layer produced across fuselage [67]. Additional work has also been done to investigate the potential for incorporating a boundary-layer ingesting cross-flow-fan into the N3-X propulsion system as an additional means for directly energizing the low-momentum boundary-layer flow [68]. The aforementioned STARC-ABL aircraft is another notable aircraft concept under development that extensively leverages BLI benefits. For this configuration, an electric fan at the aft section of aircraft fuselage ingests the large boundary layer produced across the fuselage surface, similar to the tail-mounted propulsion system commonly found in submarines [14]. Experimental and numerical work has also been performed to assess the effects of BLI on propulsion system performance and inlet distortion challenges [69]. Finally, the over-the-wing configuration used by the Airbus E-Thrust and Lilium Jet aircraft propulsion systems also utilize BLI as a performance-improving mechanism through the ingestion of the boundary layer produced across corresponding wing surfaces.

The use of wingtip-mounted propulsors has also been identified as a means to produce beneficial aero-propulsive coupling of DEP systems in conceptual aircraft configurations. Miranda and Brennan used a vortex-based potential flow method to show that a propeller mounted at the tip of a wing could interact favorably with the wing trailing vortex system to realize a net decrease in operational energy requirements for the aero-propulsive system [70]. A diagram of the vorticity model used in this analysis is shown in Fig. 15. If the propeller was mounted ahead of the wing leading edge with a rotational direction opposite to the wingtip vortex direction, the propeller-induced swirl acted to reduce the circulation strength of the shed vortex wake, resulting in reduction of induced drag. If the propeller was mounted behind the wing trailing edge with rotational direction the same as that of the wingtip vortex, this benefit was due to an increased propulsive efficiency from the pre-swirl at the propeller produced by the wing trailing vortex wake. The idea of using a wing-tip leading-edge mounted propeller for wake circulation mitigation has been used in the design of the NASA X-57 aircraft to provide thrust during cruise and to reduce the induced drag of the aircraft simultaneously [71].

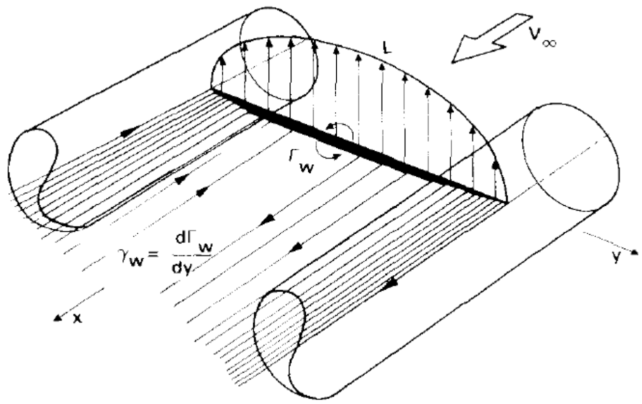


Fig. 15. Vortex model used in model of wingtip-mounted propulsor, from "Aerodynamic Effects of Wingtip-Mounted Propellers and Turbines," by Miranda, L. R., and Brennan, J. E. [70]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

There are also many concepts which take advantage of the interaction between the inlet or exit mass flow from a propulsion unit and the aerodynamic surfaces on the vehicle. One previously-described implementation of this effect was utilized in the design of the X-57 aircraft, where an array of wing leading-edge mounted propellers are used during takeoff and landing to increase the dynamic pressure over the wing and thereby increase the aerodynamic loading of the wings for low-speed flight. This approach drastically reduces the required wing area, allowing a more efficient sizing of the wing for cruise [72]. Other concepts which fall into this category are those which intend to utilize some form of thrust vectoring, circulation control, or a blown control surface or flap for high lift.

The precise aero-propulsive coupling effects introduced by integrating a propulsor within or in close proximity to an aerodynamic surface have historically been difficult to predict and simulate using low-order methods traditionally used in design. These influences of aero-propulsive coupling are a strong function of propulsor integration location and orientation, thrust level, and the shape of the aerodynamic surface itself, making it difficult to broadly generalize the influence of aero-propulsive coupling on aircraft performance. However, previous studies have been conducted to better understand and characterize these complex influences. One noteworthy study among these is that of Wick, et al. [73] where a variety of ducted fan/airfoil integrations were investigated numerically. In this study, a large parametric sweep was conducted for varying DP integration configurations across a notional transonic aircraft platform. The performance influence of over-wing, under-wing, and embedded propulsors were identified using a robust thrust-drag bookkeeping method, and DP systems were shown to be capable of as much as an 8% increase in transonic cruise efficiency over conventional uncoupled propulsion systems. Additionally, experimental work has been performed by Rolling Hills Research Corporation (El Segundo, California) and the University of Illinois at Urbana-Champaign to characterize the aero-propulsive coupling effects on an array of ducted fans mounted on the upper-surface trailing edge of an airfoil section [74, 75]. An image of the airfoil test article used in this study and resulting influence of uniform throttle across all five electric ducted fans on the airfoil lift and drag performance are shown in Fig. 16. This study was able to classify the changes in the aerodynamic performance produced by aero-propulsive coupling into three contributions: (i) direct addition of the fan thrust to the forces and moments across the body; (ii) changes in the trailing-edge boundary condition brought about by the jet efflux, leading to circulation-based changes in the pressure distribution; and (iii) aerodynamic shaping of the body due to changes in boundary-layer characteristics across the fan inlet or nozzle streamtubes.

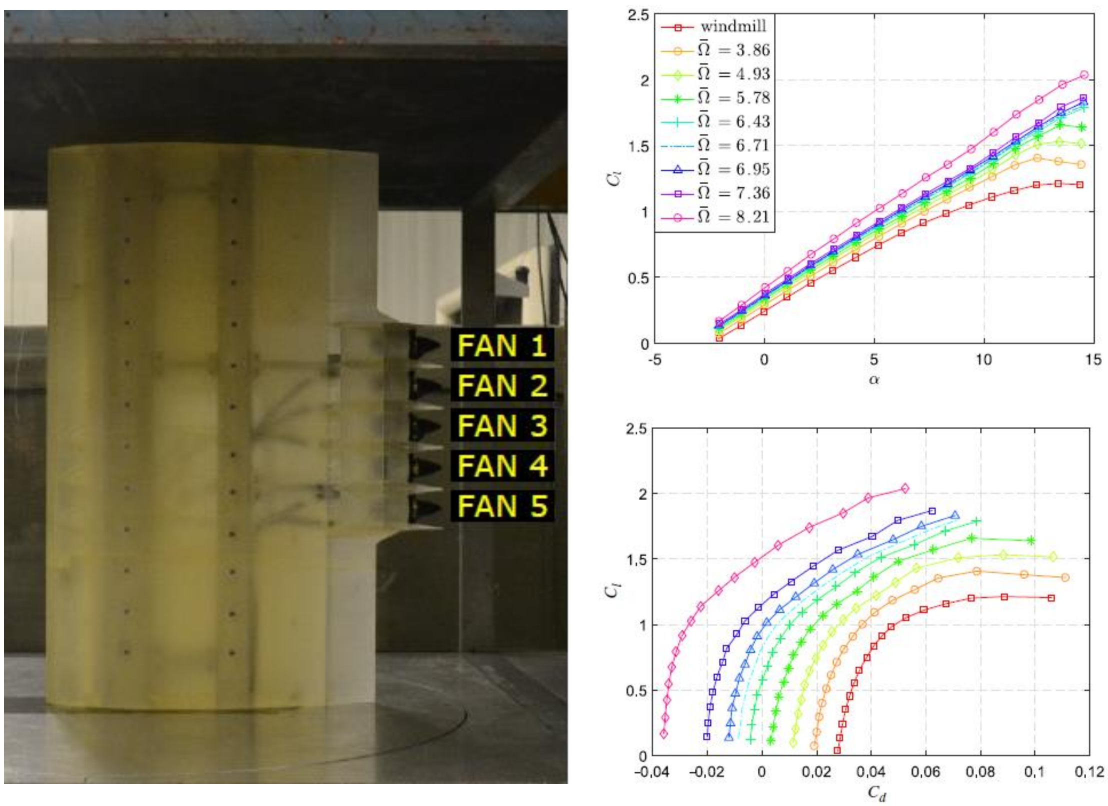


Fig. 16. Aero-propulsive coupling experiment: five-fan test article and resulting lift and drag airfoil performance, used with permission by the University of Illinois at Urbana-Champaign, Urbana, Illinois [75].

VII. Distributed Electric Propulsion Enabled Vehicle Control

While the majority of DEP aircraft concepts have been motivated as a means to improve propulsive efficiency or augment vehicle capabilities through aero-propulsive coupling, distributed propulsors across an aircraft can also be utilized as a means to perform vehicle attitude control. The propulsion-based control approach can be used to either augment the authority of conventional surfaces for control, as is the case for the NASA GL-10 aircraft [76], or to completely replace conventional surfaces, as exemplified by the Lilium Jet. Regardless, the use of distributed propulsors for vehicle attitude control provides the potential to either reduce vehicle weight or as a means to improve the fault tolerance and safety of conventional aircraft attitude control methods. The propulsion-controlled aircraft (PCA) concept originally emerged in the 1990s, in the developments following the 1989 United Airlines Flight 232 accident in Sioux City, Iowa [77]. During this flight, a DC-10 aircraft (McDonnell Douglas, now The Boeing Company, Chicago, Illinois) experienced a failure in the tail-mounted engine, which resulted in a loss of hydraulic fluid, and subsequently, loss in all control authority of the control surfaces. The flight crew utilized manual differential throttle control across the pylon-mounted engines in order to regain control of the aircraft and manage what is widely accepted as a successful crash landing. While subsequent studies into PCA [78-83] demonstrated that the concept was possible, use of this approach for vehicle control was also associated with a number of challenges.

The PCA idea is conceptually simple, assuming that isolated propulsors are utilized and any resulting propulsive-airframe integration aspects are neglected. Individual propulsors produce a thrust force vector in the aircraft coordinate system which, when applied at a distance from the aircraft center-of-gravity position, can be expected to produce a moment at the center-of-gravity location and an associated angular acceleration. Excluding certification difficulties, one of the most significant challenges preventing the feasibility of a PCA system was the long time-constant of actuation for turbofan engines, representing the time between a commanded throttle input and the resulting change in thrust output. However, with the emergence of DEP systems, the PCA concept becomes much more feasible. While the actuation time-constant of turbomachinery is known to be quite long, many of the electrical machines used for DEP systems are associated with much shorter time-constants. The improved flexibility in propulsor placement enabled by the use of electrical power transmission also enables propulsors to be placed in locations across the aircraft for the purpose of increased influence on the aircraft forces and moments.

The benefit of using distributed propulsion to enable vehicle control was suggested by Winborn [3], Ko et al. [84], Kim and Saunders [85], and Kim et al. [55]. These authors indicated that the use of distributed propulsion as a means to provide control capabilities of the vehicle dynamics could potentially lead to the elimination of traditional control surfaces. Such a case would permit, for example, a reduction in the size or complete elimination of a vertical tail surface, resulting in a substantial reduction in aircraft weight. However, the benefits and feasibility of using DEP for directional stability and control are strongly dependent on the specific aircraft class, tail weight, mission and propulsion system requirements, and certification needs being considered. For example, when DEP system architectures were considered for the ECO-150 [49], the additional propulsion system sizing constraints imposed by yaw capability requirements incurred a penalty of 1000 kg, while elimination of the tail only saved 250 kg and eliminated 2% of the overall vehicle drag. Additionally, failure-mode certification requirements play a role when considering the use of propulsion units to supplement or replace traditional methods. These requirements were also investigated for the vertical tail sizing of the ECO-150 [86]. Results indicated that architectural changes to power distribution could mitigate failure modes which produced high levels of adverse yaw at the cost of increased power-electronic weights. The reduction in vertical tail size did not offset the weight penalties associated with the redundant power architecture, although the improved safety considerations still presented this configuration as a viable option.

In contrast, a study by Leifsson et al. [87] also utilized DEP for directional control in a BWB aircraft design concept, where distributed propulsion would be used with thrust vectoring to replace elevon surfaces. Use of this system demonstrated a reduction in the total wing weight. Ko et al. [84] also indicated the positive benefit of increased control redundancy permitted with the use of distributed propulsion, wherein a propulsor-out scenario is less critical to the aircraft performance due to the increased total number of propulsors. Such a propulsor-out scenario can be more easily accommodated through a re-allocation of the thrust allotment from the other propulsors in the system. Nguyen et al. [88] also viewed the use of distributed propulsion as a means to control and improve the aerodynamics of an aircraft by leveraging propulsion-induced aeroelastic responses. Use of DEP for vehicle control has also remained a fundamental aspect of several ongoing eVTOL efforts, including the need for considering propulsive effects when balancing forces and moments during hover and transition of the GL-10 UAV, as well as the use of a pair of tail-mounted electrically-driven propellers for pitch control [76].

Although DEP-based control has been suggested, there has been limited published work which has contributed toward the theoretical development of aircraft dynamics models to enable flight controllers to take advantage of DEP. Nevertheless, several DEP-enabled aircraft have flown and demonstrated the use of propulsion for flight control, such as a scaled demonstrator version of the Aurora LightningStrike, a scaled demonstrator version of the Lilium Jet, and the NASA GL-10 UAV. While the methods which went into the development of the dynamics models and controllers for the LightningStrike UAV and Lilium aircraft are not public, the development of the GL-10 dynamics model has been published [76]. The dynamics of the GL-10 were identified through extensive wind-tunnel testing, which made use of design of experiment (DOE) methods. This approach allowed the influence of 23 different independent variables on the system to be identified without the need to survey the entire parametric space. These variables utilized in the DOE included traditional control surface deflections, as well as changes in the thrust output of the distributed propulsion system which consisted of leading-edge mounted propellers on the wing and horizontal stabilizer.

Experimental system identification, whether through wind-tunnel or flight testing, can be viewed as the current state-of-the-art approach to produce dynamics models which enable DEP-based control. The method was used by Perry et al.[89] to understand the role of embedded propulsors as control effectors on a DEP UAV. The experimental flight research vehicle developed through this study was labeled the Aircraft for Distributed Electric Propulsion Throttle-Based Flight Control (ADEPT-FC), which was based on an unmanned, 21 percent-scale Cirrus SR22T aircraft. The main tractor propeller system for this aircraft was replaced with a distributed series of eight electric ducted fans across the wing upper-surface and trailing-edge region. A photograph of ADEPT-FC is shown in Fig. 17 [90].

Fig. 17. ADEPT-FC aircraft: 21 percent-scale Cirrus SR22T distributed electric propulsion testbed for propulsion-based control, used with permission by University of Illinois at Urbana-Champaign, Urbana, Illinois.

VIII. Distributed Electric Propulsion Enabled Noise Reduction

One of the added benefits of employing DEP concepts to air vehicle systems is the possibility of reducing community noise during take-off and landing phases of flight. For turbofan systems currently used in large transport-class aircraft, the bypass ratio plays an important role in dictating associated noise levels. For the case of a TeDP concept, the eBPR of the propulsion system can be increased well beyond those associated with modern turbofan systems. This ratio, defined as the ratio of mass flow rate of all combined air flow entering the TeDP fans over that entering the engine core, can be configured in a candidate design through adding or removing electrified propulsors from the concept. Increasing the effective bypass ratio is known to reduce the overall noise produced by the propulsion system, especially fan noise. For example, Manneville et al. [91, 92] proposed the use of a mechanically linked distributed propulsion system via shafts and gears on a BWB aircraft to enable an eBPR of 20, which led to substantial noise reduction relative to a baseline aircraft. For the N3-X concept vehicle with a TeDP system, the eBPR at the rolling takeoff condition was about 30, which would provide significant reduction in fan noise relative to a traditional aircraft design. To assess the total noise reduction provided by the TeDP system, a system-level analytical prediction of certification noise was performed on two N3-X variants [93]. The first is a concept where the distributed fan nozzles are used with thrust vectoring capabilities for pitch control, rather than the large elevon control surfaces located aft of the propulsor slot nozzle used for pitch control. The resulting analysis showed that this version is estimated to have a Chapter 4 cumulative margin [94] of 32 EPNdB, well short of NASA's far-term noise goal of 52 EPNdB. The second N3-X variant configuration addressed the loudest noise sources from the first variant by moving the wing-tip mounted turboelectric generators to the inboard region of the airframe to take advantage of noise shielding effects, or by providing acoustic treatment within the long inlet and nozzle mounted inside the center-body airframe. This approach resulted in a Chapter 4 cumulative margin of 64 EPNdB, exceeding NASA's noise goal by 12 EPNdB.

One additional simple advantage of DEP for noise reduction is the lower acoustic impact of electric machines, as compared to conventional turbine-based systems. Recent studies on large electric motor systems found that noise generation from electrically-driven motors are substantially lower than that associated with compressor, combustor, and turbine components. Furthermore, the noise generation from the electrical motor system alone was found to be 8-20 dB lower than that of the fan noise for a regional jet-sized aircraft, and 17-29 dB lower than that of the fan for a single-aisle commercial transport class aircraft [95]. For another large, conventional tube and wing transport configuration, ESAero briefly addressed the noise issue on a dual-use commercial and military transport with STOL capability [16]. The TeDP configuration for this vehicle was associated with an eBPR of about 20, and the high-lift capability was supplemented by the embedded-wing propulsors. This high-lift augmentation enabled the aircraft to take off and land on short runways with steeper departure and approach angles, which further reduced community noise. For the NASA X-57 flight demonstrator, several papers were presented on the acoustic aspect of the distributed propeller system mounted across the wing leading edge [96-98]. In particular, Nark and his colleagues used multiple computational fluid dynamics codes to assess the aerodynamic performance of the configuration and then used the results to predict the isolated high-lift propeller noise source [97]. In another paper by Rizzi et al., the results of a psychoacoustic test on the X-57 DEP configuration was performed to characterize various factors that affect human annoyance by the multiple propellers interacting with the high-lift capable wing [99].

An additional advantage of the enhanced flexibility in the placement of propulsors enabled by DEP is the ability to leverage noise shielding of airframe surfaces or noise-reducing effects of boundary-layer ingestion [6, 100]. For example, Posey et al. [101] leveraged a DP system on a twin-fuselage platform and projected a low-frequency ($f \leq$ 320 Hz) reduction in noise of 20 dB across large community areas. A similar noise shielding approach was utilized in the development of the Quiet Short-Haul Research Aircraft developed by NASA [102-106]. Flight-test results from this research aircraft campaign demonstrated noise levels of 90 EPNdB as measured at a sideline of 500 ft, which for the time was considerably lower than comparable jet transport aircraft [103]. These aircraft development efforts have also been aided by historical and more recent efforts toward predicting and modeling noise shielding effects of PAI [107-113].

IX. Challenges Associated with Distributed Electric Propulsion Vehicles

Although DEP-enabled vehicles may provide new degrees of flexibility in aircraft designs and unprecedented enhancements in performance, there are a number of technology and operational challenges that must be addressed to fully introduce such vehicles into production. As noted in Sections IV and VII, due to the usage of high-power electric devices within the primary propulsion system of the aircraft, the safety challenges associated with such electric systems present potential hazards to other aircraft subsystems as well as to the occupants in the vehicles, unless the system is designed and configured with proper solutions in mind at the beginning of the design process. Furthermore, since most DEP-enabled vehicles have a highly integrated propulsion system with the airframe, there are other additional problems that arise, as identified and presented in this section.

Some configurations, such as the NASA STARC-ABL or the Airbus E-Thrust concept, utilize DEP to enable BLI benefits, which act to increase the overall performance of the propulsion system. However, the irregular or distorted inlet inflow in front of a rotating fan can be problematic, both aerodynamically and structurally, for an electric fan ingesting the airframe boundary-layer flow. Typically, inlet distortion is measured in total pressure recovery in the radial and circumferential directions at the fan face, but the flow angularity entering the fan face station is another parameter that also becomes important for highly distorted inlet inflow. In order to address distortion problems with BLI inlets, a transonic wind-tunnel experiment was conducted at NASA GRC using a distortion-tolerant fan housed in a partially embedded nacelle that ingests the natural wind tunnel boundary layer as the inlet inflow [114]. An image of this distortion-tolerant fan test hardware in a wind tunnel is shown in Fig. 18. The results of this test indicated that the designed distortion-tolerant fan was robust structurally in the presence of distorted inflow and may provide additional benefits in terms of propulsive efficiency on future aircraft. Some non-BLI propulsion systems, such as the split-wing concept used in ESAero's ECO-150 configuration, provide augmented high-lift capabilities via super-circulation through a redirection of the spanwise jet flow at the distributed exit nozzle. However, in an event of one or more propulsor failures by the closely-installed DEP propulsors, the failed propulsors can create undesired flow disturbances to the surrounding areas and affect not only the performance of neighboring propulsors, but also the aerodynamic performance of adjacent wing or other airframe surfaces. Additionally, if the fan-induced super-circulation effects are necessary for low-speed operation of the vehicle, the failure of one or more propulsors could produce an operational challenge for safe takeoff or landing phases of flight. For either BLI or non-BLI inlets, it is therefore critical to design the DEP system to accommodate non-uniform inflow conditions to minimize the effects of distorted flow in the performance of a DEP propulsion system.

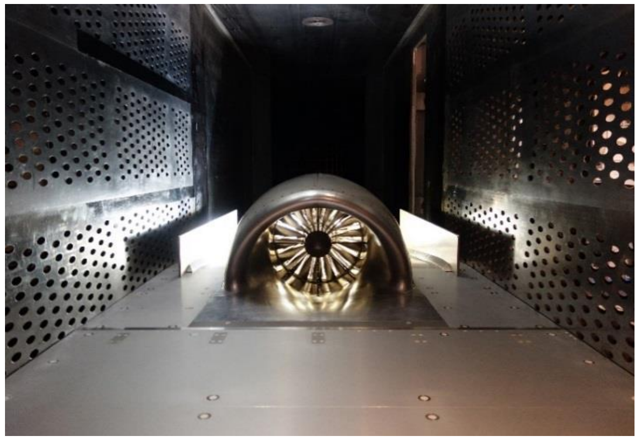


Fig. 18. Distortion-tolerant fan test article installed at NASA GRC.

For eVTOL configurations, noise generated by the propulsion system to surrounding buildings and the broad community is a major challenge in operating the vehicle in a city environment. To tackle this problem, some DEP aircraft concepts employ a larger array of smaller rotors with lower tip speeds, rather than a smaller number of large rotors with higher tip speeds, to decrease the noise associated with propeller tip vortex noise. In some situations each propulsor in a given DEP system may rotate at slightly different speeds from each other and effectively distribute the noise spectrum across a broader range frequencies to reduce the overall noise perceived by the surrounding community.

For DEP systems utilizing a significant degree of battery systems for energy storage, designing an electric power distribution system or grid is very challenging, as described in Section IV. For a battery-powered propulsion system, the applications of such a system are currently limited to short-range small aircraft such as eVTOL air taxi concepts, due to the relatively low specific energy of current battery technology. There are, however, a few other battery-powered conventional takeoff aircraft, such as NASA's X-57 aircraft and Eviation's Alice regional aircraft, but these aircraft are still constrained to short range capabilities due to limitations in battery specific energy. There are also several thermal challenges associated with use of battery systems that must be considered before a battery ESS can be certified. The thermal management measures often required to prevent or contain thermal runaway of battery cells can lead to significant reduction in the pack-level specific energy of the battery system, as compared to the cell-level specific energy. In addition to the use of electric generators and batteries, there are also concepts that employ fuel cells as the primary electric power source, but again, due to insufficient development of these technologies for flight readiness, there are only a few aircraft concepts that are currently being studied [115].

X. Conclusion

Distributed Electric Propulsion (DEP) is a disruptive concept with the potential to introduce substantial improvements in future air vehicle performance, efficiency, and robustness. This concept utilizes a distribution of electrically-powered propulsors across a vehicle in order to provide the required thrust for flight, as well as additional advantages, such as reductions in energy usage and noise, associated with synergistic propulsion-airframe integration. Due to the growing popularity of this concept, a number of platforms for testing and simulation have recently been developed to study various DEP drivetrain components and architectures. A number of DEP aircraft concepts have also been introduced across an array of platform scales, including those used for large-scale commercial transports, regional transports, general aviation vehicles for urban air mobility, and unmanned aircraft platforms. These aircraft have also been developed across a wide range of conventional take-off and landing, short take-off and landing, and vertical take-off and landing operational capabilities.

One of the commonly-cited advantages of DEP systems is the ability to utilize boundary layer ingestion benefits for improved propulsive efficiency and reduced turbulent kinetic energy losses in the wake of the vehicle. Additional aero-propulsive benefits also include the use of blown surfaces to locally increase dynamic pressure across aerodynamic surfaces, as well as modifications to aircraft induced drag through interactions between wingtip propulsors and a wing trailing vortex system. The use of DEP to enable vehicle control also provides new avenues to replace or augment control capabilities provided by traditional control surfaces. By utilizing propulsion-based control, the sizing of traditional empennage surfaces can be decreased to reduce aircraft weight, or the distributed nature of propulsors can be used to provide control assurance under critical faults and failures of other systems for vehicle control. Ongoing studies are being performed in order to provide a basic understanding of how tightly-integrated propulsors can be utilized in an aircraft control architecture, given the strong coupling between the aerodynamic performance of a local airframe surface and the thrust level of an integrated propulsor. DEP systems can also be used to reduce aircraft noise, relative to current air vehicles, particularly during takeoff and landing phases. In TeDP configurations, the decoupling of the power-generating components of the conventional propulsion system and the thrust-producing components can enable very large effective bypass ratios of the propulsion systems, since the propulsors are only electrically coupled to power-producing engine cores. These high effective bypass ratio systems can lead to substantial reductions in vehicle noise, relative to conventional designs, and strategic placement of propulsors can also be used to take advantage of noise shielding effects of airframe surfaces.

While DEP systems are currently being implemented on small-scale unmanned or passenger air vehicles, additional developments in component-level electrical systems technologies are required before such systems can be implemented on large-scale vehicle concepts. Current research is being conducted to improve the rated power capabilities and specific power of electrical machines and power electronics, relative to current levels. Additional work has also been performed to better understand strategies for power distribution and circuit protection. While power distribution systems for DEP vehicles can be quite complex, they also offer an unprecedented amount of flexibility and adaptive capabilities at the system level. Before achieving widespread production, however, there are several challenges inherent to DEP systems that are being addressed through current research efforts. These challenges include the influence of inlet distortion on fan efficiency and structural robustness, strategies for noise abatement, and the low specific energy of current battery technologies for energy storage.

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