THINGS FLIGHT TESTERS SHOULD KNOW ABOUT ELECTRIC ENGINES

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As a follow on to the white paper "Things Flight Testers Should Know About Batteries", this paper explores some of the unique challenges of testing aircraft powered by electric powertrains. Aircraft, installation, and system level topics are discussed, and critical interface considerations are included. Additionally, system integrity, performance determination, and safety-in-use considerations are detailed. An introduction to recommended instrumentation and control systems is provided. Onboard and remotely piloted architectures are considered, as well. Overall, this paper reinforces that the legacy foundations of flight testing are solid, and details how to build upon time proven approaches to safely assess novel propulsion technologies.

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1 Introduction

The recent introduction of new electric technologies in aircraft propulsion is enabling a renaissance in aircraft design not seen for decades. Free of the constraints of traditional powerplants and fuel systems, designers are developing a wide range of new aircraft configurations from distributed propulsion (e.g. eVTOL such as Wisk [1]) to conventional retrofits (such as the magniX eCaravan [2]) and hybrid systems mixing legacy propulsion with new technologies, most notably being demonstrated in NASA's Electric Propulsion Flight Demonstrator (EPFD) program [3]. All of this innovation requires careful engineering and verification through ground and flight testing in the realization of a safe and viable end product, bringing with it a range of new challenges to the flight test environment and to flight test practitioners.

The role of a flight tester is to safely and efficiently gather quality data to verify requirements to show that the system can accomplish the desired mission parameters as designed. Recently flight testers have been challenged with applying legacy hazard analyses and flight test techniques to new and novel technologies, often incorporating high levels of complexity, unfamiliar architecture, and a high level of software driven functionality. Additionally, flight testers are dealing with maturing technology, an emerging regulatory environment and the development of industry standards resulting in a range of approaches from different developers.

This paper will provide insight into the technology for the development of a flight test program for electric propulsion systems and clearly show unique areas of focus that can be applied to specific situations. Basic principles of operation of electric machines for propulsion will be explored and some of the unique applications that are emerging and important differences from a fight test practitioners' perspective will be highlighted.

For the purposes of this paper and to adhere to nomenclature in FAA FAR Part 33 [4] and the special condition issued to magniX [5], the authors will refer to electric motors and the system as "engine".

2 Principles of Flight Test

Traditional flight test programs are planned and conducted using industry standard practices and guiding principles that have been developed over the many decades. These principles are rooted in the understanding that identification of hazards and their mitigations require a deep understanding of the systems under test and their expected behaviors.

In a traditional flight test program, strong emphasis is placed on hazard identification and mitigation, from early in the development life cycle of the program to the build up of the flight test program and each test card. Flight test engineers will seek to understand the system under test and any potential hazards that may be expected, particularly during envelope expansion phases of the program, while test pilots must have a thorough understanding of the systems on board and their behavior to identify potential hazards in flight before they put the aircraft or crew in any danger.

This often requires great skill and attention and a deep technological understanding of the systems under test.

With the surge of interest in alternative propulsion systems, such as electric engines, come new hazards that may potentially challenge the flight test team to rethink how new technologies fit into traditional workflows. These existing flight test principles, methods and techniques are still applicable to these new and novel systems. When building a flight test program around an electric engine, processes for instrumentation, build up, hazard identification and data analysis are relatively unchanged. There are unique characteristics of operation for electric engines, which may vary depending upon the nature of the engine, but methodologies and techniques used to keep a flight test program safe like understanding the systems, sub-systems and components, planning for build up by using data from models and lab simulations, and implementing a thorough hazard analyses, are still used as steppingstones to the execution of flight test.

Conventional engines at this point are more or less variations of previous versions, whereas an electric engine is decoupled from traditional aircraft system integrations like bleed air, hydraulic power or electrical power. Mechanically, electric engines are simpler, but the integration and governing of the torque is more complicated, often involving fly by wire software in the loop control. There are new systems associated with electric engines that come with their own failure modes and hazard mitigations like the battery management system, contactors and software. Understanding the systems, sub systems and individual components is especially important with electric engines. First because of the new and novel nature of these propulsion systems, but also because the hazards and failure modes are also new. At some level of evaluation, the test team will have to address malfunctions that include partial loss of power, in addition to complete loss of power, or a failure to respond to control inputs. However, the sources of hazards in electric engines can be significantly different from turbines or reciprocating engines.

Figure 1 shows the risk matrix from FAA order 4040.26B that many flight testers use when performing hazard assessments. After the initial identification of a hazard, mitigations are put in place to lower the overall risk.

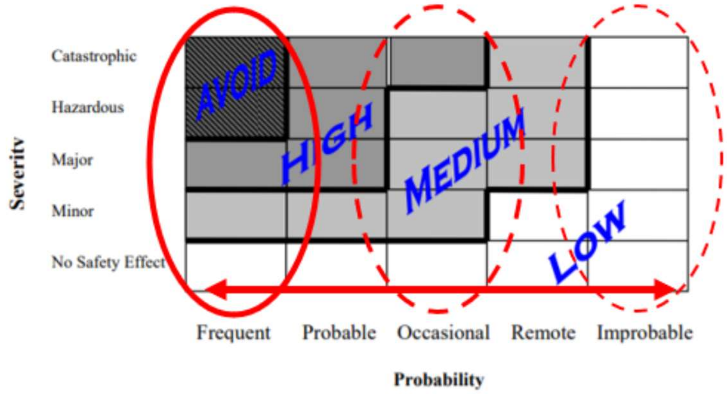

Figure 1: FAA Order 4040.26B Risk Matrix

Applications of System Theoretic Process Analysis (STPA) to identify hazards in flight test are becoming more and more frequent. Compared to traditional methods of identifying hazards, STPA can potentially find more component interaction, software and human hazards. However, regardless of how a hazard is identified, the underlying understanding of the components, sub-systems and system is required to conduct the analysis and application to flight testing.

3 Principles of Operations for Electric Engines

3.1 Defining an Electric Engine

As is the case for every component used on commercially fleeted aircraft, electric engines are required to be predictably safe; meaning that all electric engines must be designed, constructed, and installed such that the operator can anticipate how, and approximately when, the electric engine will fail. This requirement ostensibly forces designers to follow regulatory precedent and industry standards, such that the end-product is comprised of all required components. Such industry standards are currently under development by various international standards organizations and examples are shown in the references to this paper; however, these have generally not been tested against actual full aircraft projects and thus should be regarded as immature. The individual components fall into three main categories: the electric engine, engine controllers (also known as inverters), and supporting equipment. Supporting equipment may include cooling systems, governor oil feed system (where a conventional constant speed propeller is fitted) and Human Machine Interface (HMI). The engine, controller and support equipment together are referred to as an electric engine or Electric Propulsion Unit (EPU).

Figure 2 shows an example of a large electric engine, the magniX magni650 electric engine, which includes a 650kW motor and four motor controllers, whereas Figure 4 shows a schematic of the entire system integration including the power source (batteries in this case) and the propeller where the mechanical power is delivered. Figure 4 shows both power and oil distribution and how the signals are routed to the HMI.

The magni650 was developed as a direct replacement for mid-size traditional Pratt & Whitney PT6 turboprop engines for electric retrofits of existing aircraft, or clean sheet designs. With regard to features that increase the reliability of the system, it is worth mentioning that the magniX engine has been designed to be fault tolerant thanks to the electric engine-specific attributes and segregation between the four segments, hence the four controllers.

The scope of this paper is limited to the electric engine and engine controllers. Later sections will address systems integration considerations for electric engines based on best practices about testing engines and their integration learnt during development phases and from programs that have been carried-out in the last decade.

Figure 2: magniX magni650

3.1.1 magniX 650 Electric Engine

The electric engine is a direct drive permanent magnet synchronous machine with four independent three phase groups, where each group is controlled by a separate three phase variable frequency inverter, referred to as a magniDrive.

As typical of electric engines, the magni650 has a stator (non-moving part of motor) and a rotor which rotates at the same speed as the propeller. The stator is liquid cooled and is wound in a multi-three phase configuration with a total of 12 phase conducting alternate-current (AC). The rotor has permanent magnets arranged on its surface.

The interaction between the current and flux produced by the magnets will generate a flux inside the motor airgap (airgap between the stator and the rotor) that is responsible for producing the torque. The regulation of the current will be used to intensify or to weaken the flux in the airgap according to the torque demand.

The engine is capable of continuously delivering up to 650kW (900 shaft hp) of shaft power at 1900RPM to drive a conventional constant speed propellor. Speed control is achieved via a traditional hydromechanical propellor governor mounted to an accessory gearbox on the front, with high pressure oil fed through the shaft to the propellor hub.

Control of the engine is achieved via a torque command received from a position sensor on the aircrafts power lever read by the magniDrives which regulate the current delivered to the motor, thereby regulating the torque on the shaft.

3.1.2 Engine Controllers

The magni650 based EPU is controlled by four independent controllers (magniDrives) shown in Figure 3. Each magniDrive is a single 3 phase variable frequency drive, converting DC power to AC current used to regulate the torque delivered to the aircraft.

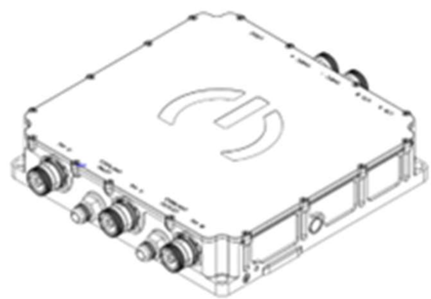

Figure 3: magniX magniDrive

The core functions of the magniDrive are:

- Motion control functions: including algorithms and strategies to switch on and off the power modules in the magniDrive to modulate AC voltage and therefore achieving the right level of current for torque control
- Protection functions: including all hardware and software protections to detect faults in the EPU
- Monitoring functions: including monitoring of critical signals that are either used for protections or for communicating to the pilot temperatures, currents, and voltages and the state compared to operational limits
- Communications functions: including CAN bus protocols to communicate to the pilot possible alerts, warning and important parameters that inform about operational conditions

The drives have multiple boards that are used for different purposes. Same board functions can be categorized as follow:

- Providing High Voltage DC (HVDC) voltage to the DC-link before it gets converted into AC voltage (the source of the HVDC voltage can either be a battery or other fuel cell)
- Converting DC voltage into AC voltage through the use of power modules

- Providing protections against lightning, especially for input/output signals (including the Low Voltage DC (LVDC) voltage
- Providing power to control units where the controllers with all the algorithms are implemented and to all the sensors

In addition to the core function of torque control, each magniDrive also acts as a health and performance monitor, with an independent condition motoring unit to ensure the accurate control of the motor and to provide error detection and communication to the HMI display. The performance monitor can also act to shut down its segment in the event of a detected failure. This dual command and monitoring functionality was a core element of system safety built into the magniX EPU.

The magniDrive is also equipped with a cooling system that is used to ensure that none of the components overheat.

4 Systems Integration

4.1 System Architecture

The architecture of the EPU (magniX eCaravan power architecture shown Figure 4) is comprised of four independent segments, each controlled by a separate magniDrive, with the remaining segments remaining fully functional in the event of the loss of a single or multiple inverters. This redundancy and graceful degradation of system performance in the event of the failure of a single component without loss of the entire engine is a key design principle employed by magniX in the development of the system, with the intent to design a system with greater levels of safety and reliability then traditional propulsion systems for single engine applications.

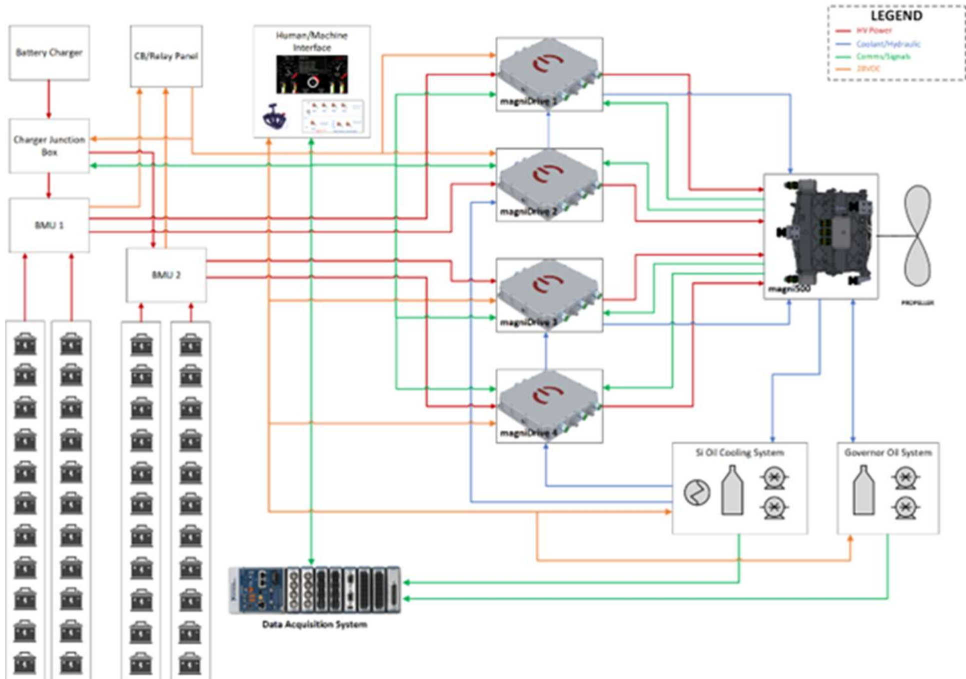

Figure 4: Electric Power Train System Architecture

From the operator's perspective, this architecture results in some significant differences over a traditional power plant. The multisegmented fault tolerant approach is more like a multiengine aircraft than a single engine one, where a partial loss of power still maintains full control over the remaining segments allowing the continuation of flight with reduced power. How much power is remaining depends on the number of remaining segments, and the flight test crew must understand the airplanes performance in the degraded condition.

4.2 Energy Sources

Electric engines can be powered from a range of sources including batteries, fuel cells, and turbo generators. Each has their own set of unique configurations, hazards and challenges that must be taken into consideration when analyzing the performance and behavior of the system.

Battery energy storage systems have to date been the most common energy source found on recent experimental platforms. They offer predictable power and behavior, though also come with a number of drawbacks, unique hazards and potential failure modes.

While the detailed analysis of the behavior of battery systems is beyond the scope of this paper, a few of the important items to consider in any new battery electric application may include:

- Battery thermal management: Battery temperatures can affect the performance of the battery and the ability of the system to deliver power as well the total energy remaining and can also be an important health indication of the battery, with elevated temperatures in part or all of the system being a cause for concern. Battery systems should be designed to self-monitor giving the number of individual cells in any single system and an aggregate temperature reported to the test crew with clear limitations established

- Hazards of lithium batteries in thermal runway and fire: Lithium batteries, when reaching a critical temperature, or under fault conditions will burn, releasing heat and gas in what's called a thermal runaway. In a poorly designed system, the heat from a cell in runaway can cause runaway in neighboring cells. Guidance for the design of battery systems and thermal runaway containment are still being established for battery systems used as primary propulsion, with existing standards such as DA311 offering a starting basis
- Relationship between state of charge and power available: When batteries reach lower state of charge, the engines may not always have full power available as when the voltage of the system drops, the current must increase for the same power, potentially encountering current limits in the system if elements of the system are not well matched
- Determining flight time remaining with state of charge requires detailed state of charge and remaining energy calculations to be made which in turn require detailed characterization of the battery system
- Hazards with electrical short circuits and handling of high voltage: Typical battery systems are designed with isolated positive and negative busses rather using the aircraft structure as a ground as with many traditional aircraft power systems. This improves safety as a short between either positive or negative of the battery bus will not affect the aircraft electric distribution system. Such systems should be fitted with automatic ground fault detection systems to identify if any shorts to ground are present due to any breakdowns in insulation

Many powertrain architectures will include more than one battery module. These may be connected in either parallel or series. A parallel multiple battery pack arrangement is inevitably lower voltage, making it less efficient and generally requiring heavier cabling (as the low voltage forces current up at the same power, and resistance losses are I^2R). However, the opposite advantage of a parallel system is that in the event of a single pack failure, voltage is maintained, and whilst there is clearly a loss of total energy capacity (and thus aircraft range and endurance), drop-off in performance should be small.

Fuel cells are an emerging technology and offer potential as a replacement for hydrocarbon internal combustion on larger aircraft. While development is less mature than battery systems, they have already seen some use in experimental systems. Fuel cells offer their own range of unique behavior and hazards:

- Hydrogen gas is hard to contain and flammable when mixed in the right quantities, resulting in the need for careful venting and gas dispersal
- Power delivery from fuel cells can have a low ramp rate, which can cause power to come on slowly when commanded if a buffer battery is not used in the system
- Fuels cells produce a lot of heat which must be managed

4.3 Human Machine Interface

Human Machine Interface (HMI) is considered the elements of the system that the humans (flight test crew) interact with, and primarily include the flight controls (engine controls) and the information displays, indications and alerts.

While the primary controls are similar to conventional power plants for engine power and propeller pitch control, how they interact with the powertrain differs as does the information communicating the state of the system to the crew.

4.4 Information Display

The magniX information display that was used in the flight deck for the eCaravan program is shown in Figure 5 below. The goal is to display information to the pilot in a succinct manner that is similar to conventional displays, however the parameters, while analogous are different nature. This display was able to provide the pilot with information on the engine segments, aggregated information from the battery, power and flight time remaining and a range of alerts in the form of CAS messages.

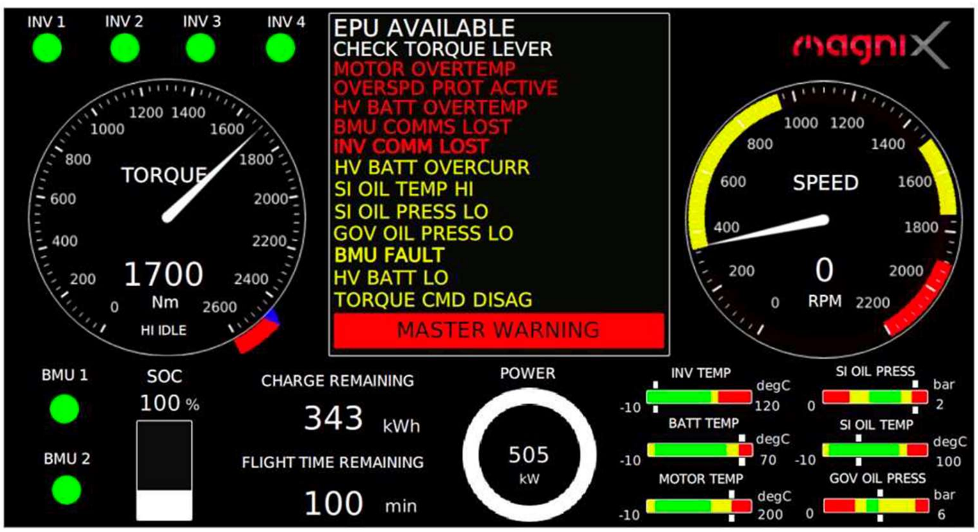

Figure 5: magniX flight deck display

Table 1 below is a sample of instrumentation parameters that would typically be included in an instrumentation parameters list and a comparison to electric engine parameters.

Table 1: Typical Turbine vs Electric Engine Instrumentation Parameters for a battery electric application

Turbine Engine	Electric Engine	Notes
Turbine inlet pressure	n/a	
Turbine inlet temperature	Stator temperature	
Turbine Speed	Rotor Speed	Same as propellor RPM if direct drive
Fuel Flow	Electrical Current	
Fuel Remaining	State of Charge	
Fuel Temperature	Battery temperature	
Torque	Torque	
Oil pressure	Coolant pressure	For liquid cooled systems
Oil temperature	Coolant temperature	For liquid cooled systems

These instrumentation parameters are a starting point when developing a flight test program on a new and novel electric engine. Instrumentation parameters must also be displayed to the pilot in an efficient and clear manner. Pilot confusion when reading data displays in the flight deck has contributed to incidents on experimental flights in the past, Reference [2].

4.5 Thermal Management

Thermal management is important in all propulsion applications. In electric engines heat is generated in the power electronics and the motor due to the electrical losses present in parts of these systems. While electric systems are highly efficient (more than 90%) compared to internal combustion engines, much of the heat in legacy systems is removed by the exhaust gas flow, whereas in electric powertrains it builds up in the internal parts of the system where electrical losses due to internal resistance and electric filed concentrations are highest.

Many aircraft will be designed to remove excess heat either through air cooling, or transfer heat to an external heat exchanger via a liquid medium. Testers must have a good understanding of both cooling systems, and their related instrumentation, for example is the cooling system cooling the main heated areas and is it being accurately measured, or is a cooling system cooling the sensor location, resulting in a failure to identify heating and potential overheating in critical parts of a system? Consulting test data from detailed ground tests containing more sensors and correlating those measurements back to measurements available in the cockpit is important in building up a picture of system performance and the value and meaning of available information.

4.6 Electromagnetic Interference (EMI)

Electromagnetic Interference is a broad term for the undesirable interaction of electric systems through the transmission of high frequency electrical noise by conduction or radiation. Many electric systems rely on measurements and sensors, which if noise levels are high such that internal filters or sensors are overwhelmed, these systems can malfunction. In Aerospace applications, equipment is tested in lab conditions to agreed standards, such as DO160G, for the levels of conducted or radiated emissions it produces.

Electric engines typically don't fall within the traditional power levels for systems found in aerospace environments, and electric engines that are driven by switching power electronics, may if incorrectly designed or installed, produce EMI level much higher than those specified in industry standards.

The establishment of standards relevant to this technology in aerospace applications is still ongoing, however flight testers must be aware of the potential side effects of EMI, and systems must be thoroughly tested during ground testing. Systems must be well bonded and grounded, and any high power interconnect cables must be well shielded to reduce the change for interference.

5 Emerging Application Space

The application space for electric engines has widened over the past few years to incorporate a variety of missions. The EASA certified Pipistrel Velis Electro [6] is fully approved for pilot training in Day VFR conditions. FAA part 23 applications ranging from 4 seat trainers like the Diamond DA40 to small commuter retrofits such as the popular Cessna 208 Caravan. Clean sheet designs such as the Eviation Alice and recently applications in FAA Part 25 regional turboprop 50-seat aircraft as large as a Saab 340 and De Havilland's DHC-7 and DHC-8. Each of these applications spaces has its own unique challenges, and ever-increasing level of complexity requires intimate knowledge and understanding of the requirements, design, and integration from the flight test practitioner.

5.1 The Emerging Regulatory Environment

In addition to the emerging technologies, the regulatory environment is adjusting to accommodate and incorporate the new aviation technologies. The FAA announced a switch in May 2022 from a 14 CFR Part 23, normal category aircraft with special conditions approach to certification to a special class aircraft certification approach under 14 CFR 21.17(b). Under the Special Class aircraft approach, a draft certification basis of each applicant's aircraft is published in the US Federal Register with a period allowed for public comment. At the end of the public comment period, the FAA addresses the public comments and finalizes the certification basis of the aircraft. This process attributes unique rules to each type design certificated under 14 CFR 21.17(b) and it can be lengthy. As of the writing of this paper, two draft certification bases for eVTOL aircraft designs have been published in the US Federal Register by the FAA.

There are also other challenges in the existing FAA regulations, like 14 CFR 27.1549 Powerplant Instruments, which outlines gage marking requirements for each powerplant. This rule is written to accommodate two, or at most maybe three, engines for a rotorcraft. If this rule were applied as written to an eVTOL aircraft design which may have upwards of 12 engines then the pilot will be overwhelmed by instrumentation and this will result in an unintended human factors impact. The applicability of these types of rules ensues from discussions each applicant has with the FAA Aircraft Certification team. The testing requirements may be different for each eVTOL powered-lift aircraft.

There are other complications arising from the Special Class aircraft approach outlined by 14 CFR 21.17(b) in that it directs use of airworthiness requirements contained in Parts 23, 25, 27, 29, 31, 33, and 35 that provide an equivalent level of safety to the specific part. However, criteria that determine level of safety are different in each part. Part 27 addresses normal category rotorcraft and Part 23 addresses normal category airplanes. The criteria that identify a normal category rotorcraft and a normal category airplane are different. Specifically, normal category rotorcraft, Part 27, are rotorcraft with a MTOW of 7,000 lbs (approx. 3,175 kg) or less and nine passenger seats or less. Whereas, normal category airplanes, Part 23, are airplanes with a MTOW of 19,000 lbs or less and 19 passenger seats or less. These elements are not yet harmonized for special class aircraft that will use elements of Parts 23 and 27 while remaining in the normal category. This may influence testing of Electric Engines in that eVTOL aircraft in a hovering environment may have to meet the transport category level of safety for rotorcraft but may only have to meet the normal category level of safety for airplanes. None of the rules address transition from hovering flight to forward flight.

5.2 Sub Part 23

The Sherwood eKub [7] is a British single seat battery-electric prototype aircraft, using a modular electric powertrain supplied by Geiger Engineering [8] in Germany. The aircraft was built with UK government funding from Innovate UK through the Future Flight Challenge scheme to develop knowledge of the routes to design, build, test and certify electric aircraft. It is a single seat with 300kg MTOW. The powertrain consists of five type 030140 3.5kWh battery packs rated at nominal 60V connected in parallel via an inlet electrical bus to a type 020300 28kW Master/Slave controller/inverter. This converts the DC battery output to a variable frequency same-voltage three-phase AC supply that controls an HPD20-30-SD-60-42-H-N single duplex motor rated to 28kW peak power at 2700rpm. (Figure 6)

Figure 6: Geiger Engineering powertrain in eKub, left to right No. 3 battery pack, controller (inverter), motor. Partially disassembled

The eKub powertrain is air cooled at the motor and controller, while relying upon thermal inertia for control of the battery packs. The motor cooling is entirely through ducting from a large inlet behind the propeller, routing air into the rear of the motor which is then exhausted centrifugally through assistance of an aerodynamically created partial vacuum (around the motor); the controller uses a smaller inlet supported by integral thermostat controlled electrical cooling fans.

5.3 Part 23

Part 23 applications broadly cover a wide range of commuter airplanes such as single engine trainers, turbine driven commuters such as the Cessna Caravan, to twin engine airplanes such as the Beechcraft King air or Beach 1900. With electric powertrains and energy storage now approaching sufficient size to power these aircraft, a number of experimental flights in this category have taken place. In addition, the surge in interest in eVTOL platforms fits under part 23, and efforts to certify these platforms have been underway for much of the past 5 years.

5.3.1 Conventional

The eCaravan project was initiated by magniX in early 2019 for the purpose of demonstrating the viability of electric powered flight though the retrofit of an aircraft of a size used in commercial applications, and to further develop the technology through integration and flight tests that would form the basis of future development and eventual type certification. The eCaravan was based on a Cessna 208B Grand Caravan, a popular 9-seat single engine PT6 turbine powered aircraft used extensively around the world in commercial applications ranging from recreation and bush flying to serving remote communities. The core technology of the electric power train was the magniX "magni500" electric propulsion system and a 258 kwh lithium battery based energy storage system.

Figure 7: eCaravan

The integration work was performed by AeroTEC at their Moses Lake facility. AeroTEC also performed all the aircraft related structural design, integration, test build up and execution. magniX provided the electric power train (engine, controllers, flight deck display, systems, battery and battery management).

The eCaravan first flew in May 2020, and throughout the program achieved three flights, with the longest being 30min, flying to a maximum altitude of 8,000ft and successfully demonstrating that electric flight of a retrofitted aircraft of this type is feasible.

5.3.2 Unconventional

From the Generation (Gen) 1 eVTOL, to the current Gen 6 eVTOL, Wisk has been evolving the design, build, and test of their EEs for over 10 years. Wisk (at the time, Zee.Aero) began its eVTOL journey with the "Lift + Cruise" configuration of the Gen 1, which had 8 vertical EEs (lift fans) and 2 aft-mounted pusher propellers. This aircraft was a proof-of-concept that eventually achieved a full transition sequence from vertical takeoff to wing-borne flight, then back to a hover and a vertical landing.

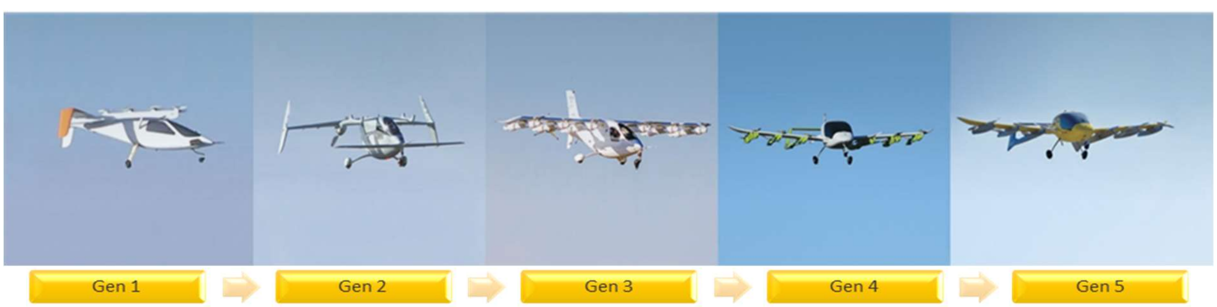

Figure 8: Evolution of Wisk (Zee.Aero) Electric Aircraft

The autonomously operated Gen 1 aircraft flew from 2011-2014, then in 2015 Wisk moved on to the onboard-piloted Gen 2 aircraft. In addition to adding the pilot to the aircraft, Wisk also removed the vertical lift fans, because the Gen 2 was used primarily to test purely wing-borne flight characteristics. Wisk moved on to Gen 3 from 2015-2017, which brought back the vertically mounted lift fans. In fact, the Gen 3 had 12 vertically fixed lift fans and one aft-mounted pusher propeller. Wisk used the Gen 3 aircraft to perform their first piloted eVTOL hover as well as a piloted transition from vertical to wing-borne flight. In 2017 Wisk began flying the Gen 4 aircraft, which, like the Gen 3, had 12 vertically fixed lift fans, and one pusher propeller. Both the Gen 4 and Gen 5 aircraft were autonomously operated "Lift + Cruise" aircraft, which allowed Wisk to explore broader airspace integration by performing autonomous off-runway flights, including transitions. Wisk used these two aircraft in over 1,300 test flights.

Figure 8: Wisk Generation 6 Aircraft

Finally, the Gen 6 aircraft combines Wisk's decade-plus of experience into a commercially viable eVTOL. The Gen 6 aircraft has 6 front tilting electric propulsion units that rotate from lift configuration to cruise configuration and 6 rear lift electric propulsion units. Wisk plans to use the Gen 6 as a self-flying air taxi, with multi-vehicle supervisors that provide human oversight from the ground.

5.4 Part 25

Part 25 transport airplanes make up by far the largest segment of the market by miles flown and by emissions produced. They range from regional transport airplanes such as the DHC Dash 8 turboprop to the long-range intercontinental jets such as the Boeing 777 and Airbus A350. This segment of the industry relies on high power turbomachinery for their powerplants. The power requirements of these airplanes are presently too demanding for the current generation of electric power trains to power them, and as such will likely be the last segment of the industry to go fully electric.

Recognizing the scale of the challenge, and the critical need to decarbonize aviation in the effort to fight climate change, NASA has partnered with industry to accelerate the maturation of electric powertrain technology to market in this megawatt class. Rather than completely replacing turbine power plants, the approach is to supplement them with electric powertrains in a hybrid configuration.

Hybrid powertrains offer the opportunity to reduce the emissions produced while still retaining useful performance, range and payload. EPFD’s two industry partners have proposed different methods of hybridization, one modifying a SAAB 340 with an inline electric motor in series with the turbine, and the other by replacing two engines on a 4 engine De Havilland Dash 7 (Figure 9) with electric powertrains, creating a parallel hybrid system. The parallel system with the electric engines powered from batteries charged on the ground has the potential to offer significant fuel savings depending on mission length while retaining the performance of the baseline airplane.

Figure 9: The magniX hybrid propulsion demonstrator as part of NASA's EPFD Program

In additional to demonstrating feasibility and maturing the technology to market, EPFD has the goal of producing the datasets required to close the gaps in regulations and standards though comprehensive ground and flight testing. Of particular focus are areas of high voltage systems up to 1000V at altitude, battery technology and safety, EMI and integration challenges.

6 Safety of Flight Operations

There is, as of yet, no standard for best practice in the regard of audible and/or light signals to imply safety or dangerous situations around electric powertrains, however some clear hazards exist that must be mitigated during testing and operation:

- The electrical hazards, particularly of battery power systems, must be carefully mitigated. Batteries are always live and in some applications DC voltages of up to 1,000 V may be present. While as discussed above high voltage installations are often isolated, there may be no clear indicators that an electric circuit is energized. Flight testers and ground support crews should become familiar with best practice for handling and working around high voltage, something not often found in aerospace work. Batteries should contain lockout-tagout (LOTO) systems, which can physically isolate them, and crews should practice verification of the absence of voltage and use of suitable tools as a routine matter.

- Unlike traditional powerplants, electric systems don’t make a lot of noise, especially when operating at low power, and indications should be used to show the system is energized and ready to start, such as aircraft clearance strobes or beacons.

- Aircraft Rescue and Fire Fighting coordination and briefing is addressed in the 2021 SFTE paper, Things Flight Testers Should Know About Batteries [9], and remains unchanged when applied to electric engines specifically.

7 Conclusion

The emergence of electric propulsion in aviation has opened the door to a new range of exciting opportunities in aircraft designs, from distributed propulsion platforms such as Wisk, to retrofits like the eCaravan and larger part 25 demonstrators like those being flown by NASA in EPFD. These new platforms and the integration of new technologies has presented novel challenges and new risks to the flight test environment, coupled with development of suitable regulations and industry standards by the regulators and standards committees as they identify, develop, and publish regulations and best practice for integrating, testing and certifying them. The pace of new technology has outstripped the pace of the guidance to flight testers and continues to accelerate. To facilitate the closure of this gap in the industry knowledge base, there is an increasing need for data, much of which relies on the safe execution of flight test to obtain.

To facilitate this demand flight testers must rely on the processes and principles that have been developed over decades of testing conventional platforms. The fundamentals of flight test and the best practices of hazard identification and analyses, ensure that these new technologies can be safely integrated, and the data generated, which will over the next decade form the bases of new standards and regulations that will guide the next generation of development and safe adoption of these technologies.

Key challenges that flight testers face in testing this new technology are:

1. Understand the operating principles of these new technologies, which differ in some cases significantly from traditional internal combustion engines.
2. New failure modes which arise from new architectures
3. The presence of high voltage and the potential for dangerous faults of energy storage systems
4. New platforms enabled with distributed, hybrid or mixed power trains and the different flying characteristics.
5. New displays and new parameters
6. Inherent complexity in fly by wire systems and the power control and energy storage levels

In this paper we have outlined some of these challenges based on the experiences of the authors working with them, giving a brief overview of the emerging technologies available, highlighted some of the unique characteristics of them and their integration into a range of platforms and discussed some of the applications space. This is by no means an exhaustive list, rather it is intended to give the reader an introduction to the possibilities and application spaces.

Electric propulsion in aviation is an exciting development, not only does it offer potential for new modes of personal and regional transportation. It is an essential evolution in the arc of aviation history, the next generation from piston to turbine to electric, promising to reshape regional transport and usher in a new generation of carbon free air transportation.

Flight testers are, as always at the leading edge of the evolution, and through their work building on the principles of their trade, the next generation of airplanes will be at least as safe and reliable as those that came before them.

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