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Safety and Certifiability Evaluation of Distributed Electric Propulsion Airplane in EASA CS-23 Category

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Abstract. Distributed Electric Propulsion (DEP) is one of the unconventional airplane architectures of interest in the quest for decreasing aviation environmental footprint. This configuration integrates strong and innovative couplings between systems and aircraft design disciplines. To address limitations of the traditional approach for certification and of the associated means of compliance when certifying innovative products, the European Union Aviation Safety Agency (EASA) issues in 2017 a novel certification philosophy that relies on high-level objective-based safety requirements. In this context, this paper presents a safety and certifiability evaluation of DEP airplane in EASA CS-23 category, with a methodology for aircraft-level safety assessment during preliminary design, a certification gap analysis with regards to existing means of compliance, and some proposals to clear the certification path for DEP configuration.

1. Introduction

Among unconventional airplane architectures envisioned to decrease the environmental footprint of aviation, the Distributed Electric Propulsion (DEP) is of high-interest for aircraft designers. Such an architecture incorporates innovative design choices. By nature, it can also integrate strong couplings between traditional disciplines of aircraft design and certification. Those couplings do not usually exist on conventional CS-23 normal category airplanes and the resulting complexity may introduce novel risks. Therefore, early evaluation of safety and certifiability concerns during preliminary aircraft design stage is of importance to ensure that the novel vehicle is safe and that obstacles on the route to certification are identified.

In this context, this paper proposes a methodological contribution to the assessment, at an aircraft integration level, of the effects of design choices on safety and certification regulation for DEP airplane. A generic configuration based on the NASA X-57 architecture serves as a basis for this analysis that is presented through a cross-analysis of high level safety driven requirements, of existing means of compliance and of safety hazards identified for such a configuration.

2. Distributed electric airplane architecture and functions

Distributed electric propulsion architecture uses multiple electrically-driven propulsors distributed about the airframe, thus distributing airflows and forces generated by propulsion system in such a way to yield a net benefit in total efficiency of the airplane [1]. The typical DEP architecture is a spanwise distribution of motor-propeller units along the wing leading edge (Figure 1, Figure 2). This synergistic propulsion-airframe integration leads to a large spectrum of possible airplane configurations, enabling new capabilities and functionalities that include: lift generation and/or augmentation by blowing wings with airflow from propellers possibly resulting in a wing area optimized for cruise; improved aerodynamic efficiency from positive interaction between propulsors and wingtip vortices; optimization of structural loads distribution; exploitation of redundancies in propulsion system; use of differential thrust for control and stability in normal or degraded modes of operations; optimization of the airplane power and energy management exploiting the possibilities offered by electric motor technologies.

Figure 1. Illustration of the NASA X-57 Maxwell DEP concept airplane (https://www.nasa.gov/specials/X57/)

Figure 2. Illustration of the Daher - Airbus - Safran EcoPulse hybrid-electric DEP demonstrator (https://www.daher.com)

It can thus be seen that, as compared to conventional CS-23 airplane architecture, a wide design space is available for designers through DEP with possible new ways to perform basic airplane functions. For the purpose of this study, a generic DEP architecture similar to NASA X-57, complemented with the assumption that differential thrust is used for lateral control of the aircraft in combination with traditional primary control surfaces and with an advanced flight control system, serves as a basis. This configuration is deemed representative enough to analyze novel hazards and failure conditions related to DEP.

3. Regulatory and certification framework for EASA CS-23 category airplanes

This safety and certifiability evaluation is conducted in the frame of the European Union Aviation Safety Agency (EASA) certification specification CS-23, the airworthiness code applicable to certify normal category airplanes.

To foster, from the airworthiness and certification point of view, the introduction of new technologies and innovations in CS-23 category airplanes, EASA released in 2017 the amendment 5 of CS-23[2], in a harmonized way with Federal Aviation Administration FAA CFR Part 23. This revision is a key-enabler for the certification of DEP airplanes. Indeed, previous amendments of CS-23 that were historically structured around assumptions based on conventional designs, prove to have become too prescriptive - thus constraining design solutions - and increasingly misaligned with the new airplanes being certified [3].

The revision of CS-23 enforces a novel certification philosophy much more adapted to introduce novelties in designs and to address existing and future vehicles. It relies on a performance-based approach supported by high level safety criteria. To appropriately consider the diversity of airplane types and operations encompassed in its scope of application, it furthermore adopts a risk-based approach and a safety continuum where safety requirements are proportionate to the complexity and performance of airplanes to certify, instead of the previous categorization based on maximum take-off mass and propulsion.

Two significant evolutions introduced in this revision are duly considered for the certifiability analysis of DEP airplane. First is the shift from very detailed and prescriptive previously existing certification requirements, to objective-based and design-independent requirements through a non-prescriptive wording. Technical solutions or design limitations are no more led or imposed by the regulation, thus opening the way to develop appropriate procedures and means to demonstrate the level of safety of innovative solutions. Second is the possibility offered to extensively rely on existing or to be developed standards as acceptable means of compliance (AMC) to safety requirements. Those standards shall contain all the necessary detailed compliance requirements. Even though issuance of AMC by aviation safety authorities remains possible, development of those standards by aviation community, e.g. through standardization bodies, or by a manufacturer is strongly promoted. As development of standards can be dynamic, this gives the opportunity to the industry and the community to come up with specifications well-adapted to given new technologies, architectures or concepts of operations. ATSM International standards for general aviation aircraft (F44) and aircraft system (F39) have been considered in the present evaluation.

4. Methodology overview

The present work aims at evaluating if a novel airplane configuration, as defined during an early aircraft design stage, is suitable from a safety and certification perspective. The evaluation allows an early interactive loop between design and safety so as to ensure a viable preliminary design for which new hazards are identified and mitigation strategies adopted, existing technical assumptions that may be challenged by innovative solutions are addressed, certification difficulties and adequate certification basis are properly anticipated.

To address and formalize this certifiability evaluation of the generic DEP configuration within the scope of the abovementioned regulatory and certification framework, an Aircraft Functional Hazard Assessment (AFHA) is first conducted as defined in ARP4754A[4] and detailed in ARP4761[5]. By analyzing each airplane functions, the novelties in the way they are implemented and the functional interactions, outputs of the AFHA are the identification of failure conditions related to DEP, their effects at aircraft level and their severity (i.e. Catastrophic, Hazardous, Major, Minor or No Safety Effect). Then, the appropriateness of certification requirements and means of compliance is assessed for the purposes of establishing a gap analysis between existing and needed requirements, and, when necessary, of formulating proposals for regulatory adjustments. Inputs from previous investigation conducted by NASA [6] for X-57 as an experimental airplane, EASA proposed special condition on Electric-Hybrid Propulsion Systems (EHPS) [7] and from EASA special condition SC-VTOL-01 [8] for Vertical-Take-Off-and-Landing aircraft that assumes distributed propulsion as a common key design driver, are used to complement the analysis of EASA CS-23 Amdt. 5 and its related AMC.

Finally, to address complexity of DEP architecture, lessons learned from this process are synthesized through the proposal of a methodology to integrate aircraft-level safety assessment for safety and certifiability evaluations combined with preliminary design activities.

5. Results of safety and certifiability evaluation

5.1. DEP Aircraft Functional Hazard Assessment (AFHA)

The following top-level aircraft functions, decomposed into sub-functions, are selected for the assessment: 1. Sustain efficient airborne flight, 2. Control aircraft speed and direction, 3. Navigation and guidance, 4. Provide power, 5. Support flight crew, 6. Provide protection and 7. Support maintenance and servicing crew activities. Phases of flight representative of a typical point-to-point trip with a small aircraft are considered for this AFHA. The exhaustive evaluation of functional failure conditions and their effects for the given generic DEP configuration, with available or assumed preliminary design information, highlights to following key findings.

First, as the DEP architecture may combine provision of thrust, lift and control, the most significant novel failure conditions are resulting from asymmetrical forces (thrust, lift, drag) across the wings, and from loss of power leading to a loss of control and a loss of powered lift. Sub-functions “Lift generation through high-lift propulsors", "Provision of lateral and directional control" and "Minimization of drag through wing-tip vortex interaction" are the most impacted by novel hazards, with severity of effects ranging from Major to Catastrophic. Second, even though it is not specific to DEP architecture, the function "Provision of electrical power" (including storage, generation and distribution) obviously presents a high level of criticality due to the cascading effects of total or partial loss of electric power on propulsive power generation, lift generation and provision of control. Third, failure conditions resulting from common modes, exposure to particular risks and cascading effects of an initial failure linked to proximity of propulsors (motors, propellers) require a detailed assessment related to design choices with regards to sub-functions for protection against lightning, electromagnetic interference, high intensity radiated field, and bird strike.

Finally, as functions and associated architectures can be designed with varying levels of complexity, it can be retained from the implementation of this AFHA that flexibility and proportionality in certification approach, safety requirements and compliance demonstration is needed to secure viable design choices.

5.2. Certifiability evaluation and certification gap analysis

The latest revision of EASA CS-23 has expanded the scope of normal category aircraft by transitioning to performance based requirements, but there is a lack of available standards to satisfy these requirements for novel designs. Demonstrating that the innovative design can be certified, operated, and maintained in an existing aeronautical environment can pose a significant challenge as design space is large. In order to move towards certification of such a system, it is necessary to consider a higher level approach towards certification.

CS-23 Amdt. 5 is analyzed to determine if the newly introduced performance objectives adequately cover the novel design features and if the defined acceptable means of compliance are directly applicable. It is desirable to use established certification methods and activities as it simplifies the process for the designer. With that goal, Table 1 presents the synthetic view of the gap analysis and the qualitative quantification of how the existing regulations, AMC and standards may be impacted to adequately address DEP in a type certification process.

Table 1. Synthesis of gap analysis for each subpart of EASA CS-23 Amdt. 5 and related AMC and standards

	Quantification of impact of DEP on existing regulation and standards	**Significant Gaps identified**
Subpart-A General	Not Impacted	No Significant Gaps.
Subpart-B Flight	Significant Impact	Lack of available performance standards to certify DEP.
Subpart-C Structures	Not Impacted	No Significant Gaps.
Subpart-D Design and Construction	Slightly Impacted	Implementation of advanced flight controls would require additional specifications.
Subpart-E Powerplant Installation	Significant Impact	Lack of available standards and specifications for electric propulsion and integration.
Subpart-F Systems and Equipment	Slight Impact	Expanded scope of Safety Assessment. Requirements for Electric Systems.
Subpart-G Flight Crew Interface and Other Information	Slight Impact	Integration of Advanced Flight Control Systems. Standards for display of required information.

The following sections describe the certification disciplines that present the most significant challenges to address.

5.2.1. Flight certification requirements. Certification of Flight characteristics involve the determination of design speeds and corresponding performances of the aircraft in established conditions, phases of flight and with probable failures. Conventionally, one of the most critical failure conditions impacting flight performance is considered as failure of one engine. The aircraft needs to demonstrate a certain level of performance and control margin in this condition. In a DEP configuration multiple scenarios exist for propulsive failures each with a different impact on the performances and controllability. To have a similar demonstration for all failure combination may not be feasible or even practical. Same reasoning is applicable for example for stall speed, minimum control speeds, take-off and landing speeds.

A conventional approach would either require extensive testing and demonstration to satisfy the conventional methodology or to force simplification of the design to reduce the level of testing required. A conservative design would mean that maximum benefit from DEP configuration will not be achievable. A similar demonstration may not guarantee safety of the design either, since the existing methodology does not consider the novel relationship between functions.

5.2.2. Flight controls certification requirements. In conventional design, the flight controls need to ensure the aircraft remains controllable in all phases of flight with probable failures which can affect the controllability. The primary factors affecting controllability are the control effectiveness due to aircraft speed and moments which reduce the control margin. One of the most adverse conditions for conventional aircraft is landing with asymmetric thrust after loss of one engine where there is an adverse moment condition on the aircraft which needs to be managed with less effective controls due to low speed.

While the overall objective remains the same for the DEP aircraft, the factors which affect the handling qualities are larger in number and with varying degrees of impact because of the complex relation between thrust and available lift. It may be necessary to manage the aircraft configuration using a suitably complex flight management system. Such a system may be a fly-by-wire system working in conjunction with the propulsion management system, the failure of which can also affect performances and certifiability of the aircraft.

Certification of complex flight control systems is not a novel concept and has been widely used in EASA CS-25 large airplane category. The Handling Qualities and Ratings Method [9] is one such example which relies on determination of the impact of failures of associated systems on handling characteristics combined with probable atmospheric disturbances. This method combines using a safety assessment to develop the systems with focused testing of the aircraft characteristics in reduced control margins to validate the design in probable failure scenarios. Such a method needs to be part of the design process at an early stage with comprehensive identification of probable failure scenarios which would need to be investigated.

5.2.3. Powerplant and Propulsion certification requirements. Distributed propulsion is only feasible using some form of electric propulsion To certify electric propulsion systems, EASA proposed the special condition EHPS [7] that offers promising elements to address the certification of an electric propulsion system as a complete system including elements at aircraft level, and not necessarily with a Type Certificate of its own as allowed by the EASA Basic Regulation.

The proposed special condition also includes requirements for supporting systems for the engines (such as fuel, electricity, etc.), which are conventionally part of the aircraft, in the electric propulsion system. The intent is to consider all elements responsible for producing thrust in the same context. This is beneficial for the DEP configuration as it simplifies the development process since these systems will also be responsible for managing lift and controllability. However, since the standards and specifications for certification of electric propulsion systems are under development this intermediate conclusion will need to be re-evaluated when they are available.

5.2.4. Flight Crew Interface certification requirements. Since an increased reliance on aircraft systems for managing the aircraft is considered, it is also important to consider human factors in operating such equipment. Usually, the pilots operating CS-23 aircraft are not dealing with complex systems. Even though digital cockpits are more common recently, the relationships between aircraft functions have remained simple. It is important to develop the cockpit environment considering such constraints. CS-23.2600 adequately set the high level safety objective for a flight deck. In order to meet these objectives, it is necessary to develop new standards for cockpit design considering novel designs with an objective to minimize crew errors resulting in additional hazards [2]. Determination of crew qualification criteria is identified as a key concern but not addressed in this paper.

6. Lessons learned and proposals

The lessons learned from the evaluation demonstrate:

- Strong interactions between systems and airplane functions (e.g. couplings between flight controls/propulsion/lift generation, multiple possible aerodynamic configurations, effects on controllability in degraded situation) that are not well addressed in AMC; this deserves a formalized interdependence analysis in safety assessment process;
- The highly integrated nature of the DEP architecture and the possible higher complexity of systems necessitate an integration of safety assessment methodologies during preliminary design stage to reach viable designs;
- Cascading effects and propagation of failures may be emphasized by the density of components necessary for the distributed propulsion (e.g. propellers and motors proximity, exposure to external events such as bird strike) and requires an appropriate analysis.

Those challenges can be addressed by taking benefit from already existing safety assessment techniques, and it is proposed to iteratively conduct a preliminary aircraft level safety and design assessment during initial design stage. The format of this assessment is derived from SAE ARP4761 and the work of Voros [10] to improve system design and safety evaluation for small airplanes.

Indeed, the safety assessment process described in the SAE ARP4761 is the most common methodology for most complex designs. This process covers majority of the factors which affect safety of the system and gives a good baseline for adapting the process depending on the complexity of the design. The same process forms the core of the proposed methodology for developing the DEP airplane. However, the key difference is introduction of some new factors which are not covered in the ARP4761 process. It is key to know that the proposed methodology will have a wider implementation in the design process and will need to start at an early design stage. The proposed approach is depicted in Figure 3.

The process starts with defining the aircraft functions which will include basic aircraft functions originating from the design and functions originating from performance requirements stated in or derived from the CS-23 Amdt. 5 and associated AMC. As an example to illustrate the latter, the following function can be derived for compliance to requirement CS-23.2120 of determining climb performance after propulsive failure: “Maintain Steady Climb gradient of 1% after probable loss of thrust”.

These functions would serve as an input for the Preliminary Aircraft level Functional Hazard Assessment (AFHA). This process needs to be started early in the design phase to minimise forced design changes due to non-compliance to certification requirement. This AFHA will be necessary to identify failure conditions which may not be acceptable regardless of their probability of occurrence.

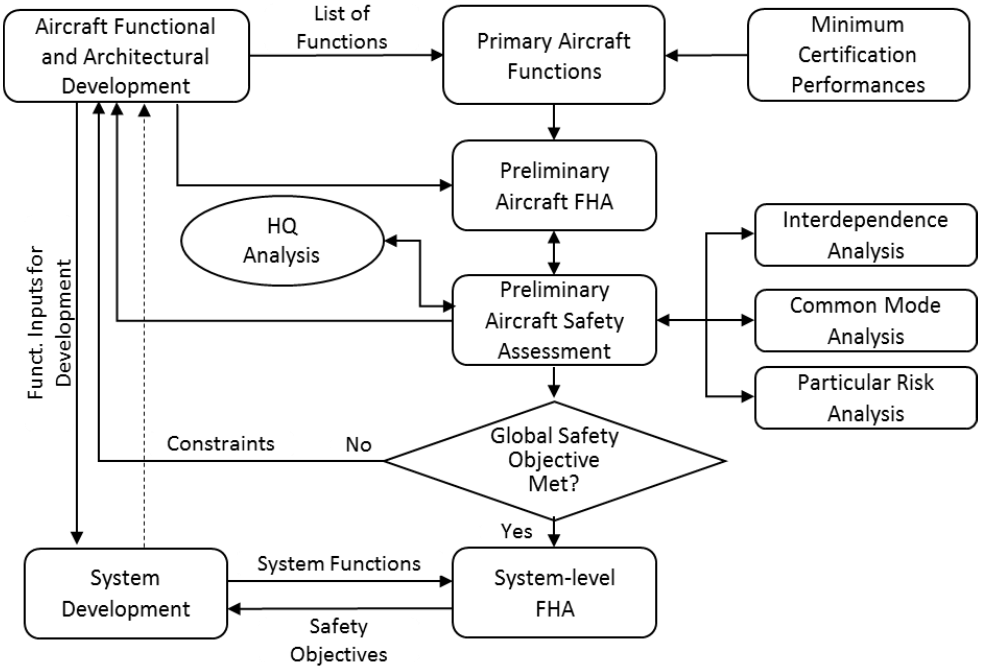

Figure 3. Proposed methodology for a preliminary aircraft level safety and design assessment.

The Preliminary Aircraft Safety Assessment (PASA) would depend on the available data for the components used in the design. At the system level sufficient standards are available for development, as well as historical data for failure rates which can be used to estimate the safety assessment process. At this stage, as a conclusion arising from the safety and certifiability evaluation of the abovementioned generic DEP configuration, the particular risk analysis (PRA) and common mode analysis (CMA) has to be complemented by an Interdependence Analysis as well as Analysis of Handling Qualities to determine that the overall design remains safe.

The remaining process would follow the conventional approach defined in the SAE ARP4761 which would require identification of design assurance levels and safety objectives for various systems and validation and verification activities carried out to verify the accuracy of the design.

7. Conclusion

DEP architecture introduces a level of complexity that is not common for small CS-23 airplanes. This paper synthesizes a safety and certifiability evaluation of a generic DEP architecture based on NASA X-57. The adequacy of the novel certification philosophy and performance-based requirements introduced by EASA in CS-23 Amendement 5 to certify a DEP airplane has been checked through a gap analysis on regulatory requirements. Further developments of means of compliance and standards are necessary to cover innovative solutions introduced by DEP and to incorporate the large available design space especially for design speeds determination, electric propulsion system and cockpit design.

To address this existing complexity, the paper proposes to take benefit, during preliminary CS-23 airplane design stage, from existing safety assessment techniques and to apply them to an integrated design – safety – early certifiability engineering practice. A generic methodology is then proposed for certifiability evaluation through a preliminary aircraft level safety and design assessment derived from SAE ARP4754A and ARP4761. Initiated during preliminary airplane design stage, this evaluation is of high interest to derisk novel architectures (e.g. functions implementation, airframe & systems designs choices) and to clear the path to certification with anticipation of challenges and development of needed standards.

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