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Conceptual design of hybrid-electric transport aircraft

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ABSTRACT

The European Flightpath 2050 and corresponding Strategic Research and Innovation Agenda (SRIA) as well as the NASA Environmentally Responsible Aviation N+ series have elaborated aggressive emissions and external noise reduction targets according to chronological waypoints. In order to deliver ultra-low or even zero in-flight emissions levels, there exists an increasing amount of international research and development emphasis on electrification of the propulsion and power systems of aircraft. Since the late 1990s, a series of experimental and a host of burgeouning commercial activities for fixed-wing aviation have focused on glider, ultra-light and light-sport airplane, and this is proving to serve as a cornerstone for more ambitious transport aircraft design and integration technical approaches. The introduction of hybrid-electric technology has dramatically expanded the design space and the full-potential of these technologies will be drawn through synergetic, tightly-coupled morphological and systems integration emphasizing propulsion – as exemplified by the potential afforded by distributed propulsion solutions. With the aim of expanding upon the current repository of knowledge associated with hybrid-electric propulsion systems a quad-fan arranged narrow-body transport aircraft equipped with two advanced Geared-Turbofans (GTF) and two Electrical Fans (EF) in an under-wing podded installation is presented in this technical article. The assessment and implications of an increasing Degree-of-Hybridization for Useful Power ($H_{P,USE}$) on the overall sizing, performance as well as flight technique optimization of fuel-battery hybrid-electric aircraft is addressed herein. The integrated performance of the concept was analyzed in terms of potential block fuel burn reduction and change in vehicular efficiency in comparison to a suitably projected conventional aircraft employing GTF-only propulsion targeting year 2035. Results showed that by increasing $H_{P,USE}$, significant fuel burn reduction can be achieved; however, this also proves to be detrimental in terms of vehicular efficiency. The potential in block fuel reduction diminishes with increasing design range – especially for low battery gravimetric specific energies. In addition, the narrow shape of the fuselage represents a volumetric constraint for the storage of the battery and typical cargo. It was concluded that the short-range/regional market segment would be the most suited for the application of such concepts. Concerning the influence of $H_{P,USE}$ on flight technique optimization, an increasing $H_{P,USE}$ was found to have a tendency of decreasing the optimum flight speed and altitude. Further investigation of more synergistic design and integration of the hybrid-electric motive power system needs to be conducted in order to explore the full benefit of such technologies.

Contents

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1. Introduction

viation today represents 2% of anthropometric carbon dioxide (CO_2) emissions [1]. Objectives for Vision 2020 of the Advisory Council for Aeronautics Research in Europe (ACARE) target an 80% and 50% reduction in nitrous oxide (NO_x) and CO_2 respectively [2]. Even more ambitious goals outlined in Flightpath 2050 [3] by the European Commission (EC) for year 2050 is a 75% reduction in CO_2-emissions per passenger kilometer (PAX.km) relative to the capabilities of conventional aircraft of the year 2000. Furthermore, a 90% reduction of NO_x-emissions and a 65% perceived noise reduction is advocated. Finally, aircraft movements on the ground have to be emission-free when taxiing. The scope of the Flightpath 2050 assessment comprises total emissions between leaving the parking position at an origin airport (off-block) and the arrival at position at the final destination (on-block). From an international perspective one can compare and contrast these EC objectives to those espoused by the International Air Transport Association [4] by way of the Air Transport Action Group [5], the International Civil Aviation Organization [6] and the US National Aeronautics and Space Administration [7]. Irrespective of the agenda or governmental office in question the conclusion is that all these targets call for a dramatic reduction in emissions over the interim-to-long term.

Targets for CO_2-emissions as originally defined in Vision 2020 and AGAPE 2020 [8] were categorized into Airframe, Propulsion and Power System (PPS), Air Traffic Management (ATM) and Airline Operations. As exemplified by Fig. 1, the Strategic Research and Innovation Agenda (SRIA) goals [9] have been re-calibrated to reflect the achievements assessed by the AGAPE 2020 report and a new medium-term goal for Year Entry-into-Service (YEIS) 2035, which is a significant point for aircraft fleet renewal. A further elaboration of the chronologically assigned CO_2-emissions targets is a breakdown that recommends aircraft energy levels (for flight including all on-board systems and services).

As shown in Fig. 2, the NASA Environmentally Responsible Aviation $N+$ series targets [7] apply to technology freeze year as opposed to YEIS espoused by SRIA and Flightpath 2050. A technology freeze year infers attainment of Technology Readiness Level [10] (TRL) 6, i.e. primed for a product development programme, and generally, an interval of at least 5 years would characterize technology freeze and YEIS milestones. If one peruses the various targets set by $N+3$, the stated fuel/energy consumption (proxy for CO_2-emissions) reduction of 60% is synonymous with the goal set by SRIA 2035. This means the $N+3$ target can be considered to be somewhat aggressive compared to the European goal in a temporal sense. A similar conclusion can be drawn when conducting a comparison of Landing–Takeoff cycle (LTO) NO_x-emissions targets.

In keeping with the review conducted by Isikveren and Schmidt [11], focusing on the SRIA goals, in order to realize a total 60% reduction in fuel burn and corresponding CO_2-emissions per PAX.km for target YEIS 2035, SRIA 2035 [9] suggests 51% from combined Airframe and PPS, and, 9% from improved ATM and operational efficiency. If one extends beyond year 2035 in order to consider a plausible strategy for Flightpath 2050, according to SRIA 2050 a possible breakdown for the total 75% reduction in CO_2-emissions would be 68% from Airframe and PPS combined, and, the remaining 7% of this 75% total from improvements through ATM and Operations. Data compiled from various investigations have shown the PPS category demands an efficiency improvement of approximately 80% over the reference year 2000 [12]. Advanced gas-turbine concepts, such as those based upon the classic Joule-Brayton cycle through intercooling and recuperation is expected to lead to thermal efficiencies of around 50% or even slightly higher, and, a further overall gain might be realized