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An assessment of distributed propulsion: Part B – Advanced propulsion system architectures for blended wing body aircraft configurations

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ABSTRACT

Studies such as those by NASA predict large performance benefits when integrating Distributed Propulsion (DP) with the Blended Wing Body (BWB) aircraft configuration. This is because the BWB planform geometry is particularly suited to the ingestion of boundary layer air. The present study evaluates the relative benefit of DP through a comparison with an advanced turbofan reference system of the same technology level as in Part A of this two part paper. Fuel savings of 5.3% relative to the reference aircraft have been shown to be achievable, although it was found that the system is particularly sensitive to duct losses.

1. Introduction

In recent years considerable attention has been devoted to novel aircraft configurations that show potential to provide a step change in aircraft performance. This is primarily driven by the high cost of kerosene fuel and demanding emissions targets set by the International Civil Aviation Organisation (ICAO) and other bodies.

NASA predicts that the combination of a Blended Wing Body (BWB) configuration and Distributed Propulsion (DP) system produces a 70–72% fuel-burn reduction relative to a B777-200LR reference aircraft [1]. NASA's quoted fuel savings figures arise from its N3-X concept, where 18–20% of the benefit is attributed to the DP system. A study by C. Lui [2] simulates the N3-X concept using a different methodology and manages to meet similar performance goals, which helps underwrite these significant benefit predictions.

NASA states the N3-X fuel burn reduction is greatly dependant on the cooling system and the type of superconducting material used. The two types of cooling system evaluated for the aircraft, Liquid Hydrogen LH_2 and cryo-cooling are most effective when coupled with the correct superconducting material. As a result both cooling systems are able to reach a 70–72% fuel burn reduction [17].

The N3-X airframe was based on the Silent Aircraft Initiative (SAI) SAX-40 design and compares a turbofan system to a DP system by fixing the airframe geometry [1]. Additional improvements may be obtained by designing a second airframe for the DP variant aircraft, where the airframe would be designed from a propulsion systems perspective.

NASA has also investigated an N+4 series of aircraft for the 2040 timeframe, including more conventional aircraft configurations with novel propulsion systems, such as those using Liquefied Natural Gas (LNG), fuel cells and hypothetical low energy nuclear power sources. The study in [18] shows a truss braced wing airframe powered by LNG with a fuel cell topping cycle reducing fuel burn by 64.1%, which exceeds the NASA N+3 60% goal.

The current study followed a proposal to investigate the overall performance benefits of DP and Boundary Layer Ingestion (BLI) technologies at an aircraft level. By analysing previous BWB and DP studies it was decided to select an appropriate aircraft class and develop a novel aircraft and propulsion system.

Both the SAI SAX-29 and its successor, the SAX-40, included three gas generators located above the fuselage mechanically powering nine fans that were semi-buried within the wing to enable BLI [3]. However, the current study was to focus on maximising fuel efficiency, and to investigate the potential of locating the gas generators under-wing. This would provide wing bending relief and enable reduced wing structural mass.

By decreasing the number of engines from three to two, the maximum thrust per engine requirement would increase, due to the required total aircraft thrust during an engine failure. Accord-

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Nomenclature

Acronyms

A	Aspect ratio
a.c	Aerodynamic Centre
AoA	Angle of Attack
BLI	Boundary Layer Ingestion
BWB	Blended Wing Body
c.g	Centre of Gravity
CD_i	Induced Drag Coefficient
CD_w	Wave Drag Coefficient
CD0	Aero Lift Drag Coefficient
CL	Lift Coefficient
DP	Distributed Propulsion
EoR	End-Of-Runway
FPR	Fan Pressure Ratio
ICAO	International Civil Aviation Organisation
L/D	Lift-Drag ratio
LNG	Liquefied Natural Gas
MAC	Mean Aerodynamic Chord
MLW	Max Landing Weight
MTOW	Max Take-Off Weight
SAI	Silent Aircraft Initiative
SFC	Specific Fuel Consumption
T&W	Tube and Wing
ToC	Top of Climb
VELA	Very Efficient Large Aircraft
V_{app}	Landing speed

Symbols

b	Span
C	Chord
D	Fan spacing
H	Fan radius
h	Gap height
r	radius
w	Width
X_A	Distance to MAC
θ	Angle
δM	Differential Moment
$\delta\alpha$	Differential AoA
Λ	Quarter-chord sweep

Superscripts

k	Kink
I, i	inner
r	Root
T	Thickness
t	Tip

ing to [3] this would have implications on the engine design such that noise would increase. Two gas generators were chosen, because the Top of Climb (TOC) thrust requirement may already be more severe than that of take-off due to the inherent high BWB cruise altitude. Maintenance costs and core efficiency losses should also be lower for a twin-engine case.

The SAX-40 favours short distances between the generator and propulsors due to the mechanical transmission system [4]. However, it may be more beneficial to use NASA's approach where superconductive electrical transmission is adopted, due to the large distances between the fans and under-wing engines. The SAX-40 also restricts the fan diameters to increase the length-to-diameter ratio to enable high noise attenuation [4], however, a more fuel efficient method could be to power an array of BLI fans by high Bypass-Ratio (BPR) under-wing turbofans. The Thrust-Split, defined as distributed fan thrust to total thrust ratio could then be optimised. In addition, the turbofan diameter would not be restricted or affected by the boundary layer total pressure distortion and aircraft integration issues. However, landing gear clearances will need to be checked.

The N3-X uses turbo-generators to transmit nearly 100% power to the DP fans [1]. Its electrical system must be sized at the most power demanding condition i.e. at End of Runway (EoR) take-off, but our study uses a combination of turbofans and DP fans to help reduce the electrical system weight. A Thrust-Split of 40% was chosen for the cruise stage but this was reduced to 20% at take-off. The climb Thrust-Split was varied so that the transmitted electrical power remained constant, to best utilise the capability of the electric system.

Ameyugo [5] examines the effectiveness of distributing small gas-turbines along an aircraft span to increase propulsive and airframe structural efficiency. However, the thermal efficiency is reported to be poor for smaller engines due to scaling effects. The electrical distribution of power to motorised fans may therefore provide a more efficient solution to enable distributed propulsion. In addition, Lui [2] reports that overall system weight reduces with an increasing number of motorised fans, in contrast with Ameyugo's [5] predicted increase in weight for small gas turbines, which get heavier due to their auxiliary systems and non-scalable parts. The success of the concept of electrical power transmission, however, hinges on the overall efficiency and power density of superconducting machines, which currently are below the required level [6]. The concept is therefore targeted for a 2035 timeframe. The aircraft may be specifically designed to efficiently carry the extra electrical system associated mass, reflecting the highly integrated nature of the DP technology.

Two methods of cooling the superconducting electrical systems exist: cryogenic cooling and cooling with liquid hydrogen. Liquid hydrogen and its required tanks are a lighter option than cryo-coolers, and the hydrogen can be utilised as a fuel after providing cooling. The hydrogen reduces the kerosene required and is lighter by a factor of 2.8, according to an earlier Cranfield University study [7]. However, the volume is approximately 4 times that of kerosene, increasing fuel tank and airframe weight. The BWB airframe is relatively spacious and more suited to the large volumes required by liquid hydrogen than a conventional aircraft, therefore liquid hydrogen is also considered in this study.

At a passenger floor area density similar to conventional aircraft of 1.4 passengers/m^2 the N3-X and SAX-40 aircraft can carry 335 passengers [8]. Other studies assess BWB aircraft of much larger capacities. The Very Efficient Large Aircraft (VELA) developed by Airbus, features four under-wing turbofans and 750 passenger [9]. However, NASA and McDonnell Douglas have investigated a number of different sized BWB designs and conclude that a payload of 800 is beyond market forecast data and cannot be accurately compared to conventional aircraft [10]. Instead, NASA developed a 450 passenger BWB and the BLI system was replaced by three above-fuselage turbofans in order to mitigate risk.

Larger capacity airframes benefit from the square-cube law, as surface area increases less than volume, thus increasing aerodynamic efficiency [10]. However, all sizes of aircraft may benefit from drag reduction through the inclusion of a BLI system. Therefore long range, medium-sized airliners show potential.