Distributed Electrical Aerospace Propulsion

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Abstract This paper investigates the development of hybrid-electric distributed propulsion system. This offers a number of potential performance benefits including improved aerodynamics, propulsion, thermal and operational efficiency (based on energy management) and increased aircraft design freedom. Airbus Group Innovations, Rolls-Royce plc and Cranfield University are working together on a UK government funded Distributed Electrical Aerospace Propulsion project. Through this project a number of models for key enabling sub-systems including Boundary Layer re-energising fan systems, higher off-take engine solutions and superconducting electrical networks have been brought together as part of an overall distributed propulsion aircraft concept model. Through an iterative design process an understanding of the design space is being established.

Introduction
Airbus and Rolls-Royce are exploring different avenues to find innovative solutions to the Flightpath 2050 challenges. This sets the targets of reducing aircraft CO₂ emissions by 75%, along with reductions of nitrous oxides (NOx) by 90% and noise levels by 65%, compared to standards in 2000. One such solution involves the investigation of a hybrid/electrical distributed propulsion system as an intermediate but necessary step towards fully electric propulsion airlines. Achieving these goals requires significant performance improvements in engine technology, systems architecture and engine/airframe integration to enable radically more efficient propulsion systems. Finding viable solutions requires that the pioneering of unconventional aircraft and propulsion technologies are continuously being improved through developments in the fields of energy storage and conversion, ultra-high bypass ratio configurations, along with hybrid electric/thermodynamic and full electric systems.

In support of the enabling technologies Airbus Group and Rolls-Royce, with Cranfield University as a partner, are engaged in the Distributed Electrical Aerospace (DEAP) project, which is co-funded by the UK government. The DEAP project is researching key innovative technologies that will enable improved fuel economy, reduced gas and noise emissions for future aircraft designs incorporating a Distributed Propulsion (DP) system architecture. This paper presents the DEAP project and findings to date.

The Benefits of Distributed Propulsion
Distributed propulsion involves the integration of several fans that are distributed across the fuselage/wing. For example, Figure 1 shows the E-Thrust concept with two clusters of three electrically powered fans across the wings and one advanced gas turbine providing electrical power for the six fans and for recharging the energy storage. There are several potential advantages of such a solution:

1) The propulsion solution can be enhanced by improving the overall aerodynamics. Effects such as boundary layer ingestion and deflected slipstream can provide drag reduction.

2) The solution allows propulsive efficiency to be increased. This is achieved by increasing the effective bypass ratio beyond the value of 12 achieved today.

3) The hybrid propulsion solution offers the possibility of maximising overall power generation efficiency by allowing the separate optimisation of thermal efficiency of the gas turbine and propulsive efficiency of the fans.

4) The hybrid-electric design supports a more-efficient flight profile as the energy management system ensures optimum power use throughout the mission cycle including the potential for windmill regeneration during descent.

5) The solution enables other aircraft design freedoms such as single engine failure scenarios. With DP the over capacity needed to mitigate single engine failure is reduced and the resultant asymmetric thrust is also reduced. This enables more advanced lower drag tail sections to be considered.

Fig. 1: E-Thrust Concept
The DEAP Project
The DEAP project objectives are to develop modelling techniques to evaluate distributed propulsion concepts and to analyse the potential of electric distributed propulsion with BLI applied to a Top Level Aircraft Requirement (including range, payload and speed) proposed by Airbus.

To deliver a DP aircraft a number of enabling sub-system models are required including a wake tolerant fan system (figure 2), a higher off-take engine with embedded superconducting generator and a superconducting electrical system.

![Distortion Tolerant Fan System](image)

**Distortion Tolerant Fan System**
The BLI fan system comprises three main components including an efficient and effective intake design, an efficient wake tolerant fan and a totally superconducting machine.

An assessment of intake losses was completed using a generic 2D CFD geometry to understand the impact of intake performance (pressure loss, distortion etc) of ingesting all or part of a boundary layer through changes to intake height and stream tube diffusion. The CFD computations were carried out by Cranfield University with steering input from the DEAP consortium.

Work is ongoing refining a 3D CFD model to better understand the important 3D effects including trades of intake performance vs number of distributed fans (duct aspect ratio).

The boundary layer ingesting fan is designed to re-accelerate the low momentum boundary layer flow. Given the non-uniformity of the ingested flow the fan design needs to be capable of withstanding distorted intake flowfields and the resultant mechanical stresses, figure 3. Through work undertaken in support of TSB DEAP by the University of Cambridge it has been shown that the fan aerodynamic losses are less than 2%.

To achieve a light-weight efficient propulsion motor solution a superconducting machine has been modelled. Through a separate Rolls-Royce lead UK government programme a totally superconducting machine has been designed and validated in a lab. The superconducting stator is constructed from Magnesium Diboride (MgB2) superconductors with a light-weight non-iron stator. The superconducting rotor consists of YBCO superconducting permanent magnets that can be flux pumped in-situ.

![Stagnation Pressure for Different distorted Flows](image)

**Fig. 3: Stagnation Pressure for Different distorted Flows**

**Higher Off-take Engine**
The engine technology has been based on the Rolls-Royce Ultrafan architecture including the “Advance” core. The low speed, low noise fan is connected to superconducting generators on the LP shaft through a power gearbox. The superconducting generator is based on the same models as the superconducting propulsion motor. The turbofan diameter has been scaled depending on the thrust being produced with the distributed propulsors.

**Superconducting Electrical System**
The baseline assumption is that the distributed fans are electrically powered through a cryogenically cooled superconducting system, figure 4. The superconducting machines and cables are rated as operating at 20K. A superconducting cable design, based on MgB2, has been undertaken by the University of Manchester in support of the TSB DEAP project. The initial electrical architecture has been set as a synchronous AC ‘tree’ architecture where the operation of the turbo is proportional to the DP fans, though variable pitch fans are considered to provide thrust/speed control and enable more effective regeneration. Initially no energy storage or alternative energy sources are assumed to enable BLI only benefits to be understood. Later in the project energy storage will be added to investigate potential energy management benefits.

Cranfield University have modelled a range of
efficiency and power density cryocoolers based on reverse Brayton cycle cryocoolers including aerospace compressor and heat sink technology. The design point study approach has started to deliver enhanced understanding of the design envelope and fuel burn trade-off with electric distributed propulsion on the proposed aircraft. Working is ongoing to develop more optimised solutions before considering the use of battery energy storage.

**Conclusions**

Preliminary conclusions are confirming the tools and techniques that have been developed to evaluate distributed and BLI propulsion systems. Further work is required to mature the various technology bricks and confirm the overall potential benefit of the approach at overall aircraft level.

**References**

2. Xiaoze, P; Smith, AC.; Xianwu, Z; Husband, M, Rindfleisch, M., Design, Build and Test of an AC Coil Using MgB2 Wire for Use in a Superconducting Machine, Applied Superconductivity, IEEE, June 2013