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FUTURE ENERGY SOLUTIONS FOR HYBRID-ELECTRIC POWERED AIRCRAFT

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Abstract

There is a growing interest in a Distributed Propulsion approach to powering commercial aircraft that replaces the traditional propulsion system. This now will consist of many smaller propellers or fans which can be located at various places around the aircraft. By far the most effective way of driving these distributed units is with electric power and this is best achieved with a Hybrid Electric Distributed Propulsion (HEDP) power system. This system distributes and manages the electrical power generated by the Gas-Turbine alternators which for larger aircraft is assumed to use superconducting electrical machines linked by a fully superconducting network. The Hybrid electric approach of this concept aligns with the current trends in aerospace industry where the More Electric Aircraft (MEA) is becoming accepted. This paper will first consider the nature of the required electrical power networks (including some of the recent developments in the superconducting technology) and then consider the nature of the superconducting power systems required. This will be carried out initially for existing MEA technology and then extended to Hybrid Electric where potential benefits in operating cycles will also be considered.

Nomenclature

A	Electric loading
AGI	Airbus Group Innovations
B	Mean flux density
BLI	Boundary Layer Ingestion
BSSCO	Bismuth Strontium Calcium Copper Oxide
BWB	Blended Wind Body
DC	Direct Current
DEAP	Distributed Electrical Aerospace Propulsion
EoR	End of Runway
E.S.	Energy Storage
GTA	Gas Turbine Alternator
HEDP	Hybrid Electric Distributed Propulsion
HTS	High Temperature Superconductors
HV	High Voltage
k_w	Winding factor
LNG	Liquefied Natural Gas
MEA	More Electric Aircraft
MgB2	Magnesium Diboride
RR	Rolls Royce
SEA	Superconducting Electric Aircraft
SFCL	Superconducting Fault Current Limiter
SMES	Superconducting Magnetic Energy Storage
SPN	Superconducting Power Network
SPU	Secondary Power Unit
T	Torque
TRV	Torque per Rotor Volume
TSB	Technology Strategy Board
V_r	Rotor volume
VFSG	Variable Frequency Starter Generator
YBCO	Yttrium Barium Copper Oxide

Introduction

The aviation industry would like to further optimise aircraft performance, increase the reliability and further decrease the costs and environmental impact of current aircraft. There is a recent interest in novel concepts regarding both the propulsive and the secondary systems of future aircraft.

Concerning the former, distributed propulsion is an approach that has become popular in recent years. In this concept the traditional propulsion system is replaced by smaller motor driven fans electrically powered by Gas-turbine alternators. A fully superconducting power network will most probably be used-allowing a lighter and more efficient propulsion system. Extensive modelling work has shown this approach is capable of delivering significant benefits due to increased propulsive efficiencies [1]. Electric power has proved to be the only effective way to achieve this configuration [2]. Figure 1 presents an example of a Hybrid Electric Distributed Propulsion (HEDP) system where several Gas Turbines Alternators (GTAs), a Secondary Power Unit (SPU) and energy storage are all used as main prime movers.

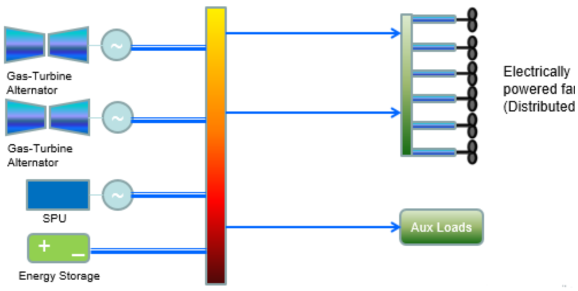

Figure 1 HEDP concept configuration example

HEDP could be considered as an evolution of the current trend of electrification of civil aircraft. The More Electric Aircraft (MEA) approach has been adopted with the main example of this concept being the Boeing 787 Dreamliner which has been commercially successful. In this concept most of the traditional pneumatic subsystems have been replaced by electrical equivalents. The introduction of a “bleedless” engine has improved both the GTA efficiency but also the whole aircraft overall performance [3]. Although successful the MEA technology has proved to be difficult to adapt to other aircraft size configurations.

In this paper, firstly a brief description of the characteristics of a fully superconducting power network will be presented. After that, MEA and HEDP concepts will be described in more detail, while the role of the hybrid operating cycles and the superconducting networks will also be considered.

Superconductivity

It was the 1911 when Dutch physicist Heike Kamerlingh Onnes first observed the phenomenon of superconductivity when he cooled mercury to the temperature of liquid helium (4K) and its resistivity suddenly disappeared. Since then several metals, alloys and compounds were discovered to have the same behavior under a specific temperature. New interest in this field was introduced with the discovery of High Temperature Superconducting (HTS) materials. Such materials remain superconducting as long as they do not exceed certain limits of current density, magnetic field and temperature.

The most well-known HTS materials are Bismuth Strontium Calcium Copper Oxide (BSSCO) and Yttrium Barium Copper Oxide (YBCO). Their high critical temperatures (around 110K and 90K respectively) make them an attractive option for our applications. However, these materials are very difficult and fragile to make, their cost is still really high and they are primarily available only in tape form. Another popular superconducting material is Magnesium Diboride (MgB2). This is a relatively cheap and robust material with high quench resistance and available in round wire form [4]. On the other hand, its critical temperature (39K) is significantly lower than the other two materials a fact that has a direct effect on the cooling power needed.

Superconducting Power Networks (SPN)

It may seem that the use of superconducting power networks

(SPNs) for an aerospace application is an illogical choice as this technology is not widely used in other, simpler, applications (e.g. ground-based power networks). However, there are reasons to believe that SPNs are in fact uniquely suited for this type of application and offer many significant advantages.

On examining the current MEA designs, it is possible that there may be some network issues preventing the expansion of this concept to aircraft of different ranges and sizes. For a different size aircraft than the 787 case the scalability of the electrical components of the network becomes the main obstacle both in weight and from an efficiency point of view. Power electronics and transmission line cables do not scale easily with the aircraft size. SPNs may be able to solve this issue. The main attributes of such a network are summarised as follows:

- *Fault control capability*

An important benefit of SPNs is their capability to quickly and efficiently control any faults that may occur. The latter is possible by using a Superconducting Fault Current Limiter (SFCL) approach. The main operational principle of these devices is that when a predetermined critical current is reached, these devices quench (i.e. lose their superconductivity) introducing a resistance to the system that reduces any fault currents before they can develop to high levels which could generate arc faults. This technology can be considered as relatively mature since it has already been used in several applications. A more optimised design for airborne applications is necessary but their performance and main characteristics are not expected to change significantly [5].

- *Current and Voltage levels*

The extremely low weight and size of the superconducting wires, combined with the elimination of design constraint of fault currents, permit the use of a relatively high normal current. This choice will subsequently lead to lower system voltages avoiding corona onset issues during cruise [6]. The true zero DC resistance means significantly higher system efficiencies and lower heat losses.

- *Switching and Power conversion*

The control and switching subsystems of these networks are expected to minimise the use of conventional mechanical switches by the use of superconducting equivalents, where local temperature and magnetic control will be implemented [7]. Power electronics in the SPNs are likely to be cryogenically cooled. Early studies suggested that certain semiconductor materials become increasingly efficient at cryogenic temperatures [8]. This increased efficiency will result in improved power and energy density. This approach also reduces the size and weight of the passive components.

- *Electrical Machines*

The volume and weight benefits of superconducting machines have been proved both theoretically and experimentally. However, the majority of existing superconducting machines are HTS rotor synchronous machines with a conventional copper stator [9]. These machines are expected to provide extra benefits if both the stator and the rotor are constructed primarily by superconducting materials. Machines with efficiency around 99.97% and two to five times better power density than the conventional equivalents should be available in the near future [10]. At the moment, this can be achieved only by using MgB_2 for the stator and any other HTS material for the rotor.

- *Cooling System*

Although SPNs offer undeniable benefits, they also add another complex subsystem. Cooling is required throughout the whole flight mission and its weight heavily depends on the efficiency and operational temperature of the several components of the SPN. There are two main approaches regarding the cooling system: either the use of a mechanical cryo-cooler or of a cryogenic fluid with a heat sink. The latter can offer significant benefits such as the use of a coolant fluid from which the boil-off gas can be used as a low emissions fuel. In addition, if this was LNG, costs would also reduce significantly.

Moreover, many recent studies have been focused on the use of cryo-coolers for aerospace applications and examples such as the reverse Brayton cryo-cooler have showed some very encouraging results both regarding their efficiency and their weight [11].

Systems Modelling

A novel approach was used in order to quantify the possible benefits of the use of SPNs in existing applications. Clearly, the weight and efficiency of these networks are key advantages for an aerospace application. In the following study a different concept will be described and investigated. This concept is a modification of the MEA approach, where the secondary power network in this case will be superconducting. In this Superconducting Electric Aircraft (SEA), the Variable Frequency Starter Generators (VFSGs), the main transmission lines and the power electronics will all be superconducting and cryo-cooled. For the weight and efficiency figures of the superconducting version two different references were used.

System Analysis-Weight Calculations

Cranfield University collaborated with Airbus Group Innovations (AGI) and Rolls Royce (RR) in a two-year UK TSB funded program looking at the Distributed Electrical Aircraft Propulsion (DEAP) concept [12]. During this program an extensive study of superconducting networks produced models and/or assumptions for the efficiency and weight of the superconducting components of our study. More specifically, models to calculate the weight of fully superconducting machines were developed in Simulink (Figure 2).

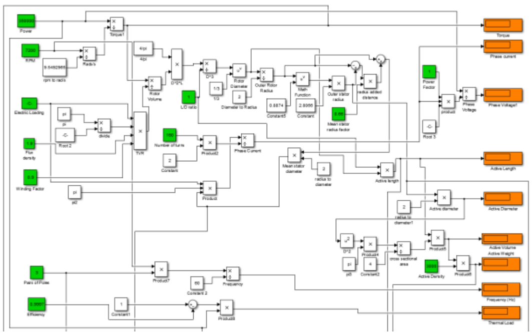

Figure 2 Simulink model of the fully superconducting electrical machines weight estimation

They were based on a conventional preliminary sizing method (i.e. Torque per Rotor Volume method) that for a given torque requirement could predict the rotor volume of the machine.

$$TRV = \frac{T}{V_r} = \frac{\pi}{\sqrt{2}} k_w AB \qquad \frac{Nm}{m^3} \qquad (1)$$

Where k_w is the fundamental winding factor, A is the electric loading, B is the mean flux density in the air gap, T the torque, and V_r the rotor volume. In order to use equation 1 anticipated values of the electromagnetic characteristics of fully superconducting machines were assumed. For a fully superconducting machine, a maximum magnetic field strength of 3T, an electric loading of 400kA/m and a winding factor of 0.9 were assumed [13].

Relatively conservative assumptions for both the power electronics and the main bus bar cables weight-that were verified during the DEAP project-were used.

The weight of the cooling system for both superconducting cases was calculated based on a two stage Reverse Bryton cryo-cooler model. Note that reference [14] (to be presented in the conference) contains an extensive analysis of the modelling of the cryo-cooling system for this type of application.

NASA has also investigated extensively the "Turbo-electric Distributed Propulsion (TeDP)" Concept. Their estimates for the superconducting components of the N3-X baseline aircraft were used as a second reference for this study [15]. The predictions being made by NASA might seem slightly optimistic compared to other assumptions (e.g. for the DEAP project).

The weight of the VFSGs in the conventional case was found in literature [16] and it should be noted that it includes the weight of their drives. In the case of the remaining power electronics weight, aerospace power electronics supplier datasheets publically available were used [17]. The weight of the cables includes the conductor, the dielectric layer, the magnetic shield, and the cooling sleeve and was calculated using information by current aerospace cables' manufacturer. Finally, as no appropriate information was available in the literature on the weight of a conventional cooling system, an approximation was made; this was that the conventional cooling system weighs 30% of the overall weight of the components being cooled.

Results and Discussion

The following figure summarises the weights of the aforementioned components of a MEA aircraft based on the size and electric load requirements of a 787 type of aircraft.

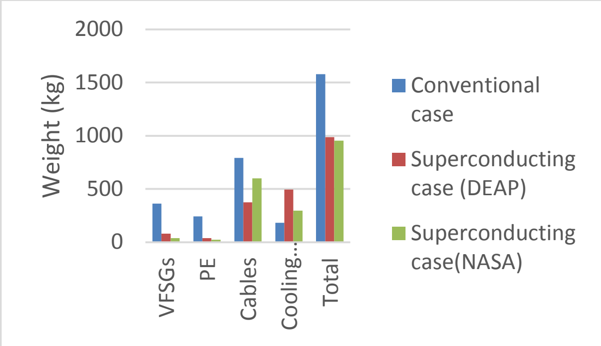

Figure 3 Weight comparison study between MEA and SEA

As expected the weight of fully superconducting generators is significantly lower than the weight of the VFSGs currently used. Based on the DEAP model (Figure 2) the generators will be more than three times lighter, whilst NASA estimates give more than an order of magnitude lighter machines. Furthermore, the expected reduction in the size of the passive parts of the cryo-cooled power electronics has led to significant weight benefits compared to the state of the art power converters. The power density of these converters is 3 (DEAP estimate) to 10 (NASA prediction) times higher in the superconducting cases. Regarding cable weights it should be noted an apparent anomaly in figure 3 derives from the fact that NASA used a 3-phase High Voltage (HV) superconducting cable that requires a substantial level of insulation as a reference [18]. This is not necessary in the SEA configuration where, as it was explained in the SPN section, a high current low voltage transmission line would be used. The weight of the required cooling system is normally considered by many as the main drawback for using SPNs in an airborne application. However, this study shows that this is not the case. The high efficiencies of the components in the SPNs reduce the heat load and consequently the cooling power demand. Based on the NASA efficiency figures, the overall weight of the cooling system in the investigated SEA aircraft is expected to be just 1.92 times the conventional cooling system of the MEA. The more pessimistic assumptions used in the DEAP project give a cooling system size more than three times (3.22 times) heavier. However, even this pessimistic weight addition is compensated by the overall weight savings.

To sum up, it can be seen that the superconducting case for an existing application proves to be lighter either using the slightly conservative estimates of DEAP project or the ones that NASA has claimed for the 2035 timeframe. Even if we assume that a weight neutral power system should be expected, the SEA will also be:

- More efficient
- Easily scalable and
- With reduced faults' impact

SPNs' use in HEDP aircraft

Whilst the use of SPNs in a MEA could be considered as optional at least for the present time, in the HEDP aircraft their use seems inevitable. There is at least an order of magnitude difference in the electric power requirements between the MEA and the HEDP aircraft as here the electric system must manage more (or all) of the propulsive power. Here the need for components with higher efficiencies and reduced weight make the use of superconducting technology essential. The DEAP program investigated the use of a SPN in HEDP type of aircraft (figure 4) where Boundary Layer Ingestion (BLI) was also used. The associated sensitivity studies showed that efficiency gains proved to be more important than the expected weight benefits of a SPN. However, there are still many aspects of these networks that have not been fully investigated and further work is necessary. Figure 4 demonstrates the proposed HEDP aircraft architecture including a SPN (superconducting electrical machines, SFCLs, HTS transmission lines) and energy storage devices.

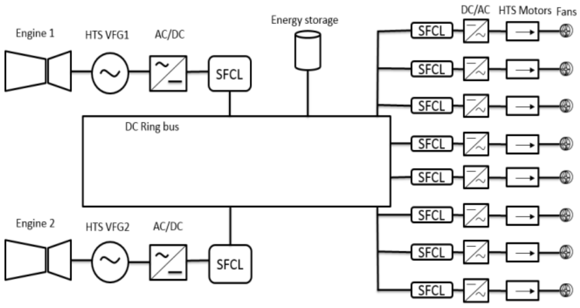

Figure 4 SPN in HEDP type of aircraft used during DEAP program

The anticipated weight and efficiency gains will be in addition to the propulsive efficiency gains possible on this type of aircraft [19]. The increased propulsive efficiency is enhanced by the use of BLI which is expected to reduce the drag of this configuration [20]. BLI could also be further enhanced by the implementation of a novel airframe such as the Blended Wing Body (BWB). In summary, the use of a "flexible" distributed propulsion system gives far more design freedom. For example, hybrid systems can offer very flexible operating cycles, something that has been already shown in other transport applications. These will be described in the next section.

HEDP Novel Operating Cycles

Hybrid configurations have also attracted the interest of other industries such as automotive and the marine. Their complex and variable operating cycles (i.e. frequent starts and stops) could be easier handled using a hybrid approach due to its enhanced flexibility. This is the main reason why electric/hybrid propulsion systems are starting to gain significant share of the market in these industries, although their power networks are more complex than the conventional equivalents.

Aircraft operating cycles may not be as variable as those of a car or a ship. However, there are still asymmetries in the flight mission that make the design of the main propulsive units challenging. For example, the safety case scenario (i.e. “one engine out End-or-Runway (EoR)” case) has an impact on the design of the GTs. Furthermore, dynamic requirements during the cruise phase (e.g. emergency operations) and the significant difference in the power demand of the various flight phases may also reduce the efficiency of the prime movers. Figure 5 summarises the asymmetric nature of a typical flight mission of a medium range aircraft.

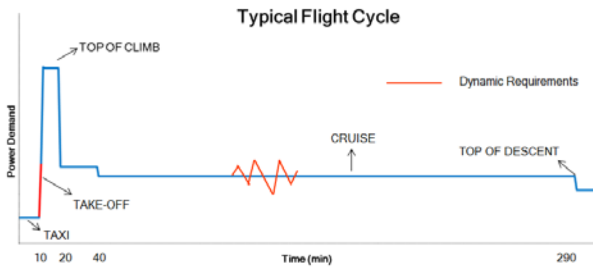

Figure 5 An example of a typical flight cycle power demand

It is clear that the anticipated benefits of using a hybrid configuration in an aircraft will not be of the same magnitude as in the other industries. Nonetheless, these benefits will be supplementary to the improvements in propulsive efficiency, emissions etc. Furthermore, the flexibility of the whole hybrid system could be further enhanced by the use of advanced energy storage.

In HEDP configurations, Energy Storage (E.S.) could be used for short periods of time dealing with some of the dynamic requirements of the flight cycle. Similarly in hybrid ships energy storage is primarily used as a boost for the demanding phases and as a power source for the dynamics of the whole mission.

In this application a mix of different energy storage technologies could be used for different functions in the aircraft. In addition to batteries, supercapacitors and Superconducting Magnetic Energy Storage (SMES) could also prove to be beneficial in a hybrid configuration. The extremely high power densities of supercapacitors could be useful for short term power peak demands and any emergency loads that need instant response. In regard to SMES, it could prove to have useful power and energy densities in the context of a SPN where it could be fully integrated into the system for minimal extra weight.

Energy storage technologies are improving rapidly and they are expected to improve even more the next few years. It is difficult to predict the exact extent of these improvements which could provide the different solutions as to the choice of the various E.S. options. It seems likely that this rate of improvement could therefore favour the use of a specific type of E.S. over the others. In case of a mixed E.S. system the integration between the different types is a complex procedure and extensive studies would be necessary to optimise the control and overall system performance.

Finally, there have been studies proposing a full electric approach where batteries are used as the main prime mover for the whole mission [21]; however, in the view of the authors, it seems unlikely that battery banks of such a high power and energy density will be available in the near term (or even medium term) future.

Conclusions

Whilst this is still early work the results suggest that Superconducting Power Networks can provide many specific advantages in Aerospace applications whether these are More Electric or Hybrid Electric power systems.

For More Electric it is likely that SPNs can be adopted without significant weight penalty and provide much greater design flexibility and performance In addition they will allow the use of new low emission (and low-cost)fuels that are also used for cooling the power system.

For Hybrid Electric Aircraft these properties of SPNs add to the values of increased power density and efficiency that are essential for these high power applications. Furthermore if SPNs were adopted by More Electric Aircraft this would make the eventual transfer to Hybrid more progressive.

However in all other transport sectors the main benefit of Hybrid Electric technology lies with its flexibility around the operating cycle and this will also apply in Aerospace. It seems likely that these cycle improvements may be less than in some other sectors (due to the nature of aerospace operating cycles) but nevertheless are likely to prove positive. Note that even modest gains in this area would add to the other benefits in propulsive efficiency gains. Furthermore any improvements in Energy Storage technologies beyond the current predictions would enhance this considerably.

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