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FULL-ELECTRIC, HYBRID AND TURBO-ELECTRIC TECHNOLOGIES FOR FUTURE AIRCRAFT PROPULSION SYSTEMS

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Abstract

Recently a huge progress in the field of electrical machines makes them more available for aviation. Assuming a big leap forward of electric technology in the near future, many research institutes around the World examine a revolutionary propulsion system which employs electrical machines. This idea can be a perfect response to a drastically growing air traffic and its demands about emission and fuel consumption reduction. There are already manufactured full electric, ultralight airplanes, which show that the technology is promising and future-proof. What is more it seems to be a key enabler for the development of the other technology that will influence the future of aircraft design and will allow introducing completely new airplane architectures. That is why Institute of Aviation in collaboration with The Ohio State University conducts investigation and analysis on feasibility of using such systems for aircraft propulsion. For this task a completely new tool based on Numerical Propulsion System Simulation (NPSS) environment is being developed. It will enable to analyse the electric devices conjugated with turbine engine as a whole propulsion system in the matter of its performance characteristics. The purpose of this paper is to present some of the most promising ideas and already accomplished analysis of different kinds of architectures. The analysis and optimization of the system, as well as cost effectiveness will be presented.

Keywords: *full electric, turbo-electric, hybrid systems, distributed propulsion systems*

1. Introduction

Historical data shows that air traffic double every 15 years in terms of Revenue Passenger Kilometre (RPK). It means that in 15 years World annual RPK will be more than 12 trillion (Fig. 1). It can be concluded that at that time also CO_2 and NO_x emission will double. In response to the growing aviation, and hence growing fuel demands and environmental concerns, a drastic improvements in the field of aircraft technology needs to be done. It can be achieved by the improvements in aircraft design and by use of more efficient propulsion systems [1].

One very promising concept of how to improve the propulsion system efficiency is to use an electric propulsion technology, which could be either full electric, hybrid electric or turboelectric propulsion. All of these concepts must have high efficiencies in convert electrical power into useable thrust with high efficiency, in order to be comparable with piston or/and gas turbine engines that they are meant to replace. This paper shows the most feasible ideas of using electric systems for aircraft propulsion and provides information about their pros and cons.

2. Different kinds of propulsion systems architecture incorporating electric components

Below are presented different types of architectures of the propulsion systems that incorporate electric components. First, the most obvious type of architecture is full-electric system. In full electric propulsion, the propulsor (either fan or propeller) would be driven with electric motor powered by battery, super conductors or other energy sources.

In the hybrid electric propulsion system, the energy to power the fan comes from the turbine engine or from the energy storage system (like batteries or flywheels). One can imagine two types

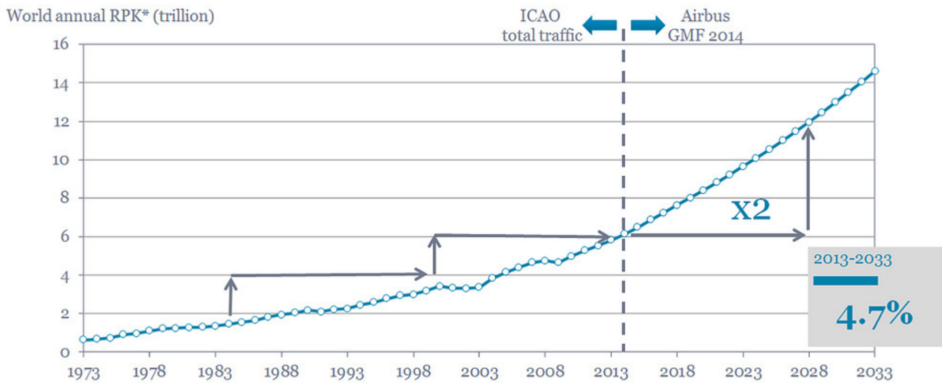

Fig. 1. Air traffic growth in terms of year's vs revenue passenger kilometre [4]

of hybrid system a parallel one and the series hybrid. In parallel, the fan is driven by either a turbine engine or an electric motor or both working at once (Fig. 2b). In the series hybrid (Fig. 2c) the turbine engine drives the generator which creates power needed to drive the fans. In addition there is also a storage system that can be used to provide power in certain stages of airplane mission to support the power created by the generator or to completely overtake the power demands (e.g. during taxi on the runway).

The last type of the possible architecture is the turbo-electric system. Basically, it consist of the same elements as series hybrid except the storage system. The fans are driven by the electrical motors and the power for them is provided only by the generator, which is constantly driven by the turbine engine. This idea, seemingly strange, has its significant advantages, with which the greatest one is the ability to use the electric system as an electric gearbox.

The chart below (Fig. 2) presents the simple scheme of full-electric and turboelectric systems as well as both listed above hybrid architectures.

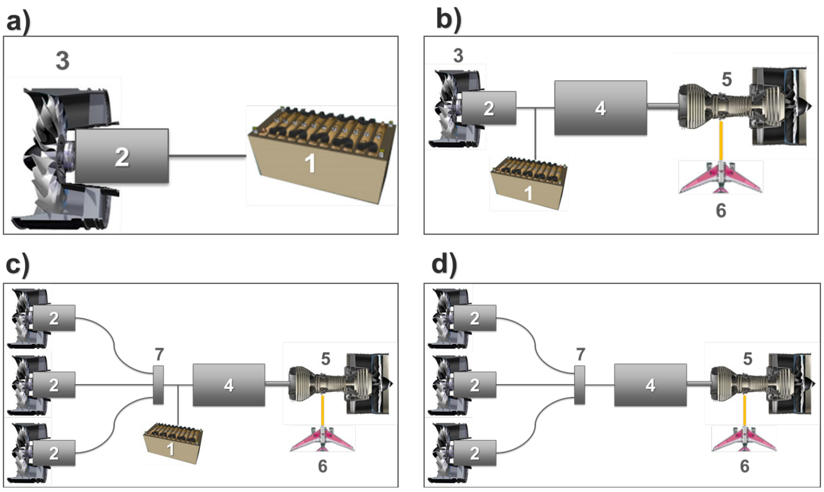

Fig. 2. Comparison of different types of architectures: a) full-electric propulsion system, b) parallel hybrid propulsion system, c) series hybrid, d) turboelectric. 1 – battery, 2 – electric motor, 3 – fan or propeller, 4 – generator, 5 – turbine engine, 6 – fuel tanks, 7 – power buss

3. Full-electric system analysis

The use of full-electric system is very attractive because of the high-energy conversion efficiency. In the picture below (Fig. 3) can be seen a comparison of a power conversion efficiency for propulsion systems which uses standard internal combustion engine (ICE) and electric motor. It can be seen that energy conversion in electric system is more than 90% versus 42% for internal combustion.

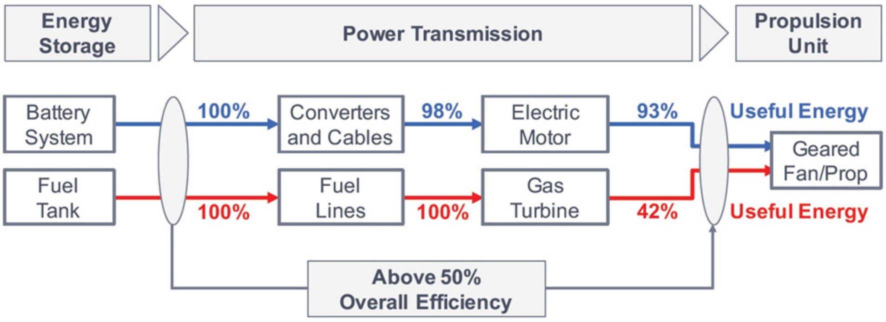

Fig. 3. Comparison of energy conversion efficiency for the electric propulsion system and for the standard propulsion system with internal combustion engine [6]

In the world, there are now several full-electric aircrafts (Fig. 4). These are mostly the ultra-light class airplanes, one or two seater. They show, however, some new solutions and many interesting conclusions can be drawn from their design. What is more according to [5] the development of such aircraft can be a perfect answer for the Small Air Transport (SAT) Aircraft Family Program ACP-1 type requirements and further evolution of this concept to meet ACP-2 requirements.

Fig. 4. Examples of full-electric aircrafts: a) Pipistrel Alpha Electro, b) E-Fan 2.0, c) Yuneec International E43, d) SportStar EPOS.

What is worth special attention is the flight time durability. For most constructions, it does not exceed 60 min. It is all because of the energy density of the storage system (batteries for most of the constructions). The energy density for the Li-Ion batteries, that are available these days, is about 200 Wh/kg for new and about 120 Wh/kg for standard ones. In comparison for Jet-A1 fuel these property is equal 12,000 Wh/kg so almost 100 times more. This huge gap between these two energy sources can be a big barrier insurmountable in case of usage of full-electric propulsion system for bigger aircrafts.

Rough calculations and analysis of the Airbus A319 (140 PAX) class aircraft performing 800 NM mission shows that with full-electric propulsion system the mass of the typical Li-Ion batteries used as an energy source would overcome 1000 kg per one passenger. While in the standard configuration with two-turbofan engines mass of fuel, (Jet-A1) equals 30 kg per passenger. This shows that usage of the full-electric propulsion system for commercial airplanes would not be possible in near future (in 30 years from now). Even with very optimistic assumption of some researchers that in 30 years Lithium-Sulphur batteries would provide us with 800 Wh/Kg energy density, the mass of the batteries would be still 5 times bigger than the mass of the kerosene. What is very important in case of full-electric propulsion system is that the maximum takeoff weight (MTOW) of the aircraft with such system is equal to maximum landing weight (MLW). This further reduces useable mass of the energy source.

4. Turboelectric system

It seems reasonable then to combine internal combustion engine, which can use high-density energy source together with electric system that has great efficiency of energy conversion. Maximizing the advantages of both systems and minimizing flaws. One of the method to do it is to use the turboelectric system. In such system, power comes from ICE (turboshaft engine) and the electric devices are used to increase the efficiency of the whole propulsion system. It is obvious that the engine efficiency is the combined result of its thermal efficiency and its propulsive efficiency dependence (1). To make engine more efficiency one has to rise one or both of them. To increase the thermal efficiency it can be made hotter (increase pressure ratio and temperature at the turbine entrance). However, these two parameters influence on NO_x emission increasing it. What is more the more sophisticated and more expensive materials have to be used and at the end the gain can be not worthy of the whole improvement.

$$\eta_{engine} = \eta_{thermal} \cdot \eta_{propulsive} \tag{1}$$

However to increase the propulsive efficiency the increase in flow kinetic energy has to be reduced. For turbofan engines, it can be obtained by making fan pressure ratio lower. However, to preserve the same amount of thrust more air needs to be pumped throug the engine. Which simply means that the bypass ratio (BPR) has to be increased. The BPR can be drastically increased thanks to the use of electric system, which role in this case boils down to being simply an electric transmission.

To overcome the additional weight of the generator, electric motors, electric system etc. the benefits should be significant. To analyse the scale of benefits, which can be achieved thanks to use of such system the thermodynamic cycle and engine mass calculation, were performed. Comparison was done for the 150 PAX single aisle commercial aircraft (A320 class). Propulsion system of the baseline aircraft, which consisted of the two state-of-the-art engines (GE LEAP class engines), was replaced by turboelectric distributed propulsion system.

Results of both systems were compared for take-off, top of climb (TOC) and cruise conditions. TOC condition was an aerodynamical design point (ADC) for the turboelectric propulsion system cycle calculations. Results, which consists, among others, the thrust specific fuel consumption (TSFC) and effective bypass ratio (eBPR) parameters can be seen in the table below (Tab. 1). Tab. 2 shows the comparison of mission total energy consumption for both systems.

As can be seen theoretical benefits achieved thanks to the much higher BPR are equal of about 20% lower energy consumption.

The next table (Tab. 3) presents comparison of total mass of the both systems. Second column presents mass calculation obtained for current state-of-the-art power densities for electric machines (6 hp/lb) while the third column presents the results obtained for power densities predicted in 30 years from now (15 hp/lb for electric motors and 30 hp/lb for generators) according to [3]. One can notice that with present electric devices the mass of the turboelectric system will be more than 17% higher than the mass of two, modern, high bypass turbofan engines. Bigger mass will overcome the benefits that come from the lower fuel consumption. However, the predicted leap forward in electric machines technology (in 20-30 years from now) can bring even 19% gain on the propulsion system total mass. Taking into account lower fuel consumption it can result in bigger payload mass of the aircraft, which directly converts to an airlines profits.

Tab. 1. Comparison of the cycles of the state-off-the-art modern turbofan engines with the turboelectric propulsion system

	Take Off		TOC (ADP)		Cruise		
Altitude	0		35000		35000		ft
Ma	0		0.8		0.8		[-]
Thrust rating	100%		100%		80.4%		[-]
Thrust	66000		12198		9802		lb
Prop. System	2 × LEAP	TeDP	2 × LEAP	TeDP	2 × LEAP	TeDP	
Core thrust	–	1740	–	71.92	–	0	lb
Core power	–	36967	–	24202	–	16490	hp
eBPR	11	30	11	28.8	11	24.21	[-]
Fuel mass flow	5.159	2.940	1.791	1.632	1.429	1.139	lb/s
TSFC	0.281	0.160	0.528	0.482	0.525	0.418	lb/(h*lb)

Tab. 2. Comparison of mission total energy consumption of state-off-the-art modern turbofan engines with turboelectric propulsion system

	2 × LEAP	TeDP
TSFC @ Cruise (M0.80, 35k ft)	0.525	0.418
Mission Energy Consumption [BTU]	4.99E+08	3.97E+08
Reduction compared to LEAP	–	–20.35%

Tab.3. Comparison of mass of state-off-the-art modern turbofan engines with turboelectric propulsion system

	2 × LEAP	TeDP	TeDP Advanced
Total Fans (lb)	–	3253	3253
Turboshaft (lb)	–	3590	3590
Electric system (lb)	–	8139	2402
Nacelle/tanks (lb)	–	3270	3270
Total propulsion system (lb)	15500	18252	12512
Mass difference	–	+17.7%	–19.3%

5. Hybrid systems

Hybrid system (Fig. 2b and 2c) might seems very attractive because it can works as turboelectric system, but also use of the batteries to support the turbine engine during the power demanding stages of the mission. There are many concepts on which stages of the flight the additional energy storage system (as batteries) might be used and in what range. Small amount of stored energy could be used to augment the power from the generators so that the turbine engines could be sized specifically for cruise and then use stored energy to augment power from the turbines to make enough power to generate the needed take-off thrust and even through the climb stage. That could reduce the turbine engine size so that it has to work a little harder. Current cruise turbine entrance temperature is much lower than it is necessary to keep the turbine life on sufficient level.

However also this concept faces constraints of poor energy density of current and forecasted for near future batteries. Batteries once used to support required power peaks would have to be carried through the main part of the flight (cruise stage) uselessly. The energy density required to overcome the energy costs required to carry the batteries during the cruise stage seems to be very high, it might be even more than 600 Wh/kg.

6. Summary

Use of the electric devices is very attractive as future propulsion systems. Key enablers that provide benefits from use of the electric system are great energy conversion efficiency of electric systems and immense electric power distribution possibilities around the aircraft body. Besides the benefits listed above these two factors enable a completely new approach to design of the future aircrafts, which introduces new opportunities to further increase of the airframe efficiency e.g. blended wing body aircrafts that uses boundary layer ingestion – possible thanks to the use of distributed propulsion system [2]. Electric systems are certainly the future of the aviation and an increasing electrification of future aircraft can be expected. However, it is currently, not possible to completely abandon the use of fossil fuels as a source of the high-density energy. Energy source with the density levels inaccessible even for the future electric energy storage systems.

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