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Electric aircraft - present and future

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Abstract
In this paper, an outlook about the present of electrical aviation is given. The relatively small energy density of current battery technologies is adequate to build usable electric car, but not suitable for electric aircraft. Because of the very limited amount of energy available on-board, a couple of percent in efficiency can give significant increase in range and flight time, hence the development of more efficient propulsion system and E-motor is as important as the development of battery technologies. Current research results at the University of Dunaujvaros show, that building E-motors from amorphous materials is possible, and can easily increase the efficiency of high speed E-motors.

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1. Introduction

Stimulated by car industry and current mainstream developments in transportation, the interest in full or hybrid electric propulsion for aircraft has grown during the last couple of years. Many scientific and general publication mentions that storing electric energy in batteries promises a clean new world with minimal environment burden, and excellent opportunities for economic growth.

The growing of air transport is clearly visible with promising future. Airbus global market forecast (Schulz, 2019) predicts, that over 37.000 new aircraft is going to be sold in the next 20 years. It is proven that air transportation is only slightly affected by global crises (Figure 1), hence long-term market prediction can be more accurate. Airbus predicts a nearly constant annual growth of 4.4% (Schulz, 2019).

This growth leads to an increased environmental impact, since more fuel is going to be used in the next term. To make aviation more environment friendly, fuel consumption must be decreased to keep (at least) the emission at a constant level. To achieve this goal, new technologies and operation schemes are needed that could possibly decrease the fuel consumption in the order of 15-20% per flight.

Besides the problem of pollution and emission, the amount of oil is limited. Taking into account the growing demand and the depletion of oil reserves, the price of crude oil has been steadily climbing for many years, following a clearly visible trend.

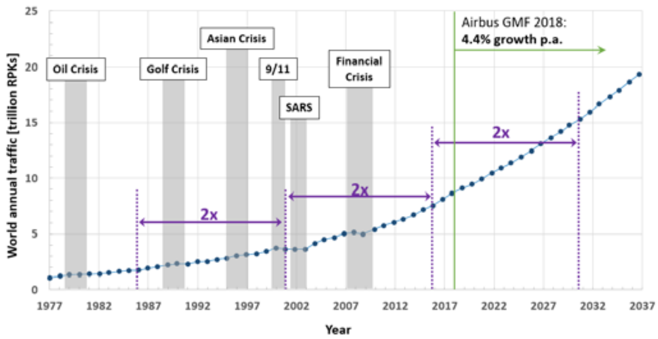

Fig. 1. RPK (Revenue Passenger Kilometres) versus time, global crises slightly affect growing, data from (Schulz, 2019)

Electric propulsion system can achieve zero emission locally (Geetha et.al., 2017). These systems benefit from better efficiency in energy conversation as well. The key question here, that can check whether it is a greener or only an alternative technology, is how the electrical energy is produced. In countries, where mainly renewable energy is used in production, electric aircraft have the advantage in terms of emission. On the other hand, if the electric aircraft is recharged with electricity produced in coal power plant, it has higher overall emission than a petrol powered aircraft. Figure 2 shows what percentage of energy is produce from renewable sources from the total electrical energy in some countries (Wilson, 2018). In this Figure, electric vehicles are more environmental friendly only in countries that are marked with green bar.

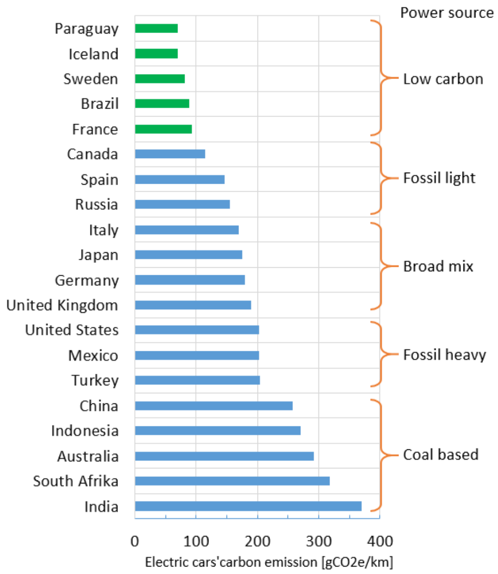

Fig. 2. Electric vehicle total CO2 emission [gCO2 / km], data from (Wilson, 2018)

Connecting renewable energy research with unmanned aerial vehicle (UAV) technology can offer more accurate measurements with higher spatial resolution and possibly lead to understand more deeply the aerodynamic effect of wind turbines (Nagy et.al, 2018). Most of the UAVs operate from electric energy stored in batteries, therefore using high speed and high efficient electric motor is greatly beneficial (Gur et.al, 2009).

Introducing electric propulsion system into ground transportation is more simple compared to the implementation in aviation. The mass of ground vehicles is not as critical as of aerial vehicles, so the additional mass of battery means less problems. Furthermore, aerial vehicles have significantly higher typical travel distance, hence storing more energy is necessary. Aerial safety standards are also extremely high, which makes the implementation of electrical or hybrid propulsion system harder.

This paper shows a possible next step in the fight for cleaner and greener aviation. Many studies focus on improving the capacity of batteries from the current circa 300 Wh/kg to at least 2000 Wh/kg which would enable fully electric airplane to be introduced in air transport (Hoelzen et al., 2018). This paper, in contrast, focuses on the possibility of increasing the efficiency of electric motors and generators, which also helps reaching higher range and flight time.

2. Aircraft electric propulsion system concepts

2.1. Fuel cell systems

This kind of system stores energy in chemical form and convert to electric energy by using fuel cells. They are used in many special applications however, they are still expensive, complex and heavy. Some research aims to imagine what could be a possible design of a fuel cell driven aircraft (Colonno et.al., 2014) (Koehler, 2008), an example is shown in Figure 3. Others make a smaller step forward by investigating the utilization of fuel cell as auxiliary power unit in more electric aircraft concept (Guida et.al., 2017; Pourabedin, 2019).

Application of fuel cell in small UAVs can also be advantageous, for example (Gadalla, 2016) states that PV cells with hydrogen fuel cell hybrid power system can increase the UAV endurance by a factor of 1.9.

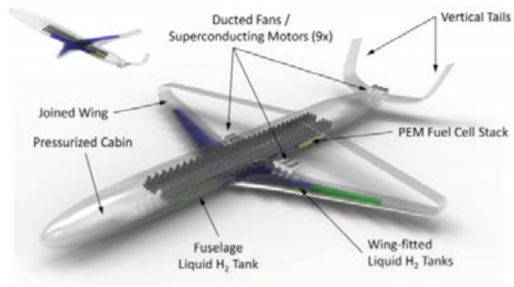

Fig. 3. Proposed conceptual design for a 180 passenger hydrogen fuel cell powered aircraft (Colonno et.al., 2014)

2.2. Battery systems

The energy in these systems is stored in batteries, which allows a direct extraction of electric energy. The chemical process of charging and discharging the batteries limits the total efficiency. Another significant limitation is the energy storage capacity of batteries, since the energy required for the total flight must be stored on-board (Bicsak, 2017).

In Figure 4, the specific energy of different battery chemists is shown and compared to fossil fuels. It can be clearly seen, that significant battery storage capacity increase must be reached before and electric airplane can compete with today's airplane in terms of range and speed.

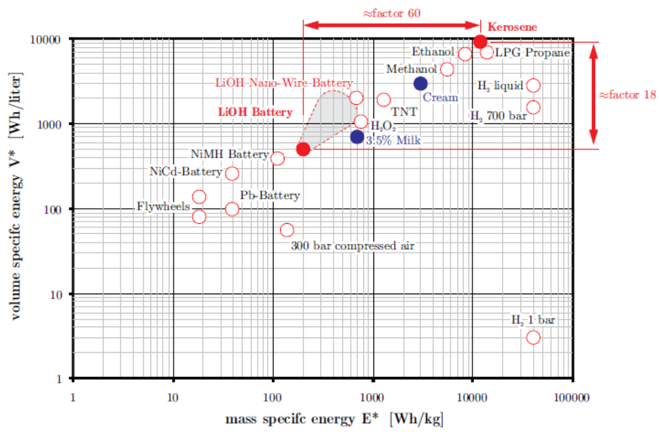

Fig. 4. Volume and mass specific energy characteristics of different energy storage systems (Hepperle, 2012)

Taking into account the battery technologies (Andwari et.al, 2017) which is the only commercially available solution for electric aircraft, one can see that Lithium based battery technology has the highest energy density today (in 2019).

Table 1 shows the present and future of some promising battery technology in terms of specific energy.

Table 1. Specific energy density of current and future chemical battery systems (Hepperle, 2012)

System	theoretical specific energy	expected in 2025
Li-Ion (2012)	390 Wh/kg	250 Wh/kg
Zn-air	1090 Wh/kg	400-500 Wh/kg
Li-S	2570 Wh/kg	500-1250 Wh/kg
Li-O_2	3500 Wh/kg	800-1750 Wh/kg

It is obvious, that even with today's most promising battery technology, the energy density remains under 1/4th of the energy density of kerosene, meaning energy efficiency of on-board consumers (mainly electric motors) is still an important factor. Alternative electrical energy storage technologies are under development as well, like hybrid battery / supercapacitor systems (Kouchachvili et.al, 2018).

The technology currently available enables the development of electric driven paragliders that are widely used as sport and recreational flying vehicle. Some research focuses on developing UAV that has flexible paraglider wing (Nagy et.al, 2012). These special aircraft have unique flying characteristics that make them an excellent choice for some application.

2.3. Electric Motor Technology

Electric motors in aviation must be specifically designed to operate continuously at rated (cruise) power. In some applications, like for hybrid cars, the electric motor is designed to operate in short power boost only, so comparison with these E-motors should be made with care. Hybrid vehicles can show their full potential only if serious energy management is implemented (Pandaya et.al, 2016) (Geetha et.al, 2017). Figure 5 shows the power density of electric motors, in comparison with piston and gas turbine engines.

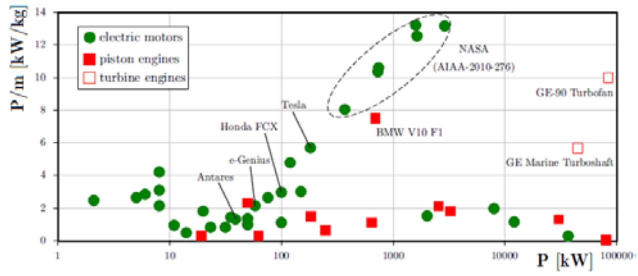

Fig. 5. Specific power density of current piston engines and E-motors (Hepperle, 2012)

Some electric motors are available today for aircraft propulsion that have output power in the 100kWs range. Large electric motors are also used in applications, where the mass is less important (like ships or trains). It is possible to build electric motors today with specific power of around 2-4 kW/kg.

To further increase the power density of electric motors, new materials and technologies must be introduced (Krings et.al., 2017; Widmer et.al., 2015). There is a strong need for E-motors specifically designed for aviation, which is lighter, more powerful and can meet higher safety requirements. Aircraft with full electric propulsion raises new issues like heat rejection problem, which further strengthen the need for better electric motors (Falck, 2017). Some studies are also suggest, that novel aircraft design is going to be required to enable the introduction of fully electric aircraft in commercial aviation (Borer, 2016). For example, the NASA X-57 experimental aircraft (Deere, et.al. 2017) (Figure 6) uses distributed electric propulsion concept, which is more suitable for fully electric aircraft than the conventional propulsion system arrangements.

Fig. 6. NASA's X-57 prototype (NASA material)

In fact, this concept is not a new idea: In the design of NASA Helios Prototype (Figure 7), (Noll et.al., 2007) which was a fully electric solar powered UAV, they used this concept as a result of extensive research and optimization. The predecessors of NASA Helios, like NASA Pathfinder (Colella et.al, 1996) are date back to the 80's.

Fig. 7. NASA's Helios prototype (NASA material)

3. Increasing electric motor efficiency

The very limited on-board energy storage capacity of electric aircraft needs more efficient propulsion system to achieve more flight time. 2-3% increase in efficiency of E-motors means at least 2-3% more flight time and range, or eventually can mean the different between reaching the next airport or not.

A research project at the University of Dunaujvaros aims to increase the efficiency of E-motors at high speed by (i) decrease the iron loss in the stator by applying amorphous materials and (ii) increase the mechanical properties of the rotor by developing new Cu based alloy.

3.1. Using of amorphous material to reduce iron loss in E-motor

Recent studies aim to apply magnetic glassy tapes to build stator elements for electric motors. There is a strong industry demand of the materials with low cost and improved mechanical and magnetic properties: lower coercive force, lower core loss and higher tensile strength. However Fe based amorphous ribbons are promising for this purpose, but in order to use these materials, several additional requirements have to be satisfied, like cutting the soft magnetic elements into the appropriate shapes, avoiding the degradation (local crystallization) of the individual glassy elements. (Koti et.al, 2018) Amorphous magnetic materials have been used in power transformers for more than 20 years, but the technology not

Cutting technology has to be adopted to make the thin ribbon forming possible. Laser cutting experimental tests have been conducted in (Koti et.al, 2018) with the following conditions:

- gas types used: Ar, O_2, He, N_2
- laser power kept at 50W
- cutting speed between: 1000 - 4000 mm/min
- constant gas flow rate: 10 liters/min

The results are evaluated based on the changing in magnetic properties of the amorphous ribbon. The research in (Koti et.al., 2018) shows, that laser cutting of amorphous materials is possible without degrading the magnetic properties of the material. Hence, our results take another step forward to build higher efficient electric motors.

3.2. Increasing mechanical properties of rotor

Electric motors with high rotational speed suffer from additional problems like rotor unbalance, bearing overload and rotor deformation. The last effect (besides others) forces the motor design engineer to increase the air gap between the rotor and the stator in order to avoid collision between them. The increased air gap provides additional loss, therefore makes the E-motor less effective.

High speed E-motor unbalance can be handled by preliminary simulation, like one described in (Hong, DK., et al. 2013). The vibration sources of rotor in permanent magnet (PM) E-motor include mostly the centrifugal force generated by eccentricity and the unbalanced magnetic forces. (Wang T. et al, 2011).

4. Conclusion

In this paper, an outlook about the present of electrical aviation is given. Unlike ground vehicles, aerial vehicles are very sensitive to system mass. The relatively small energy density of current battery technologies is adequate to build usable electric car, but not suitable for electric aircraft. It seems that the technology is not going to enable the replacement of current propulsion technologies in the near future; however, some forward-looking projects want to prove the technology.

Electric motor efficiency is high compared to piston engines or gas turbines. However because of the very limited amount of energy available on-board, a couple of percent in efficiency can give significant increase in range and flight time, hence the development of more efficient E-motor is as important as the development of battery storage technologies.

Current research results at the University of Dunaujvaros show, that building E-motors from amorphous materials is possible, and can easily lead to increased efficiency in the future. In this paper, some electric aircraft technology and applications are also discussed.

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电动飞机 - 现在和未来

關鍵詞
电动飞机
混合飞机
无定形材料
电动机开发

摘要
在本文中，给出了关于电气航空现状的展望。 目前电池技术的相对较小的能量密度足以构建可用的电动汽车，但不适用于电动飞机。 由于船上可用的能量非常有限，效率的百分之几可以显着增加航程和飞行时间，因此开发更高效的推进系统和电动机与开发同样重要。 电池技术。 Dunaujvaros大学的现有研究结果表明，用非晶材料制造电动机是可能的，并且可以很容易地提高高速电动机的效率。