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ELECTRIC AIRCRAFT PROPULSION

Elektryczny napęd dla statków powietrznych

Abstract: *This paper presents the state of the art in electric aircraft propulsion systems. The necessary reduction of greenhouse gas emissions on the global scale forces aviation engineers to search for 'green' solutions. Electric aircraft propulsion is a potential and relatively intuitive choice for a reduction of emissions in flight operations. This paper showcases four architectures of aircraft propulsion systems being now considered to utilise the advantages of electric propulsion with commercially profitable operating range and payload capabilities. One of the largest technological obstacles to the widespread use of electric propulsion in aviation is the low energy density of modern electric batteries. This paper presents the types of power supply which may achieve an energy density above the minimum threshold of 500 Wh/kg, and alternative onboard electrical power sources. The paper also shows novel designs of electric motors intended for aerospace applications. The final sections of this paper shows the implemented projects of aircraft with electric propulsion and the electric aircraft propulsion research projects underway around the world.*
Keywords: aircraft engine, aircraft, electric power supplies, electric propulsion, hybrid propulsion

Streszczenie: *Artykuł przedstawia stan wiedzy z zakresu elektrycznych systemów napędowych statków powietrznych. Niezbędna redukcja emisji gazów cieplarnianych na globalną skalę wymusza poszukiwanie ekologicznych rozwiązań. Zastosowanie napędu elektrycznego to potencjalna i stosunkowo intuicyjna metoda redukcji emisji. W artykule przedstawiono cztery architektury systemów napędowych, które rozważa się obecnie do wykorzystania o komercyjnie opłacalnym zasięgu roboczym i możliwościach masy użytecznej. Jedną z największych przeszkód technologicznych w powszechnym stosowaniu napędu elektrycznego jest niska gęstość energii nowoczesnych baterii elektrycznych. Zaprezentowano zasilacze, które mogą osiągnąć gęstość energii powyżej minimalnego progu 500 Wh/kg oraz alternatywne pokładowe źródła energii elektrycznej. Przedstawiono również nowatorskie konstrukcje silników elektrycznych przeznaczonych do zastosowań lotniczych. W końcowej części artykułu opisano realizowane projekty statków powietrznych z napędem elektrycznym oraz realizowane na całym świecie projekty badawcze dotyczące elektrycznych napędów lotniczych.*
Słowa kluczowe: silnik lotniczy, statek powietrzny, zasilacz elektryczny, napęd elektryczny, napęd hybrydowy

1. Introduction

For the aviation sector to achieve climate neutrality by the year 2050, action must be taken to reduce the emission levels of greenhouse gases from hundreds of thousands of aircraft. Air transport generates more than 900,000 tons of CO_2 a year, which is 2.5% of the global carbon dioxide emissions and 12% of the total emissions in the transport sector [6]. High-altitude emissions support the greenhouse effect, while the contrails (condensation trails) from jet engines have been proven to have a major, added impact on global warming in that they increase cloud coverage. Although the aerospace industry can boast that the CO_2 levels per passenger-mile have been reduced by more than 50% since 1990, the increasing demand for passenger flight service has been increasing the CO_2 emission levels. The reduction of emissions in aviation is now based on two methods. One method is to specify the optimum aircraft engine performance parameters (fig. 1). Another method is to apply novel combustor solutions [1] and novel types of aviation fuel [3].

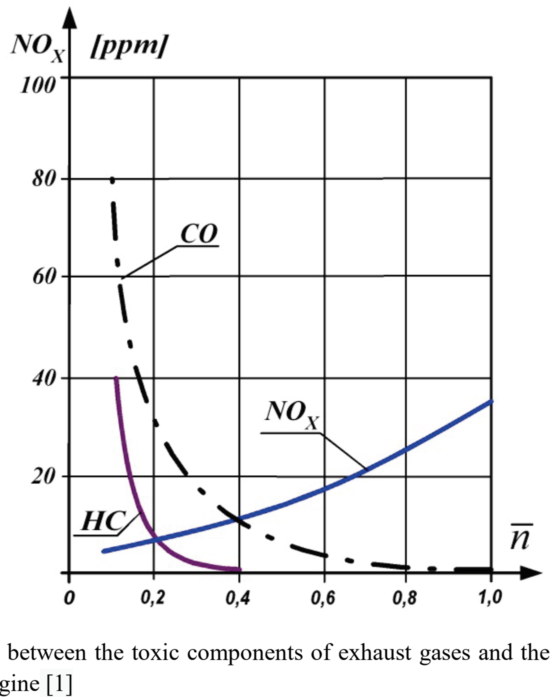

Fig. 1. Relationship between the toxic components of exhaust gases and the performance range of a turbojet engine [1]

A radical solution to the aviation emissions would be a shift to electric aircraft propulsion. The performance of aircraft combustion engines largely depends on the concentration of oxygen in the ambient air, which changes with the flight altitude. The operating performance of electric motors does not vary with altitude. Servicing and maintenance of electric motors is much faster, easier and cost-efficient by virtue of their simpler structure.

The structural simplicity translates into a higher reliability of electric motors. Electric propulsion systems do not suffer from carburettor icing, contaminants, or water in aircraft fuel tanks. While the low temperatures at high altitude have a certain negative impact on electric batteries, it is much easier to heat them than to supply more oxygen to a combustion engine; the heat energy for the batteries can be tapped from the cooling cycles of electric motors and their control systems.

Lower gas emissions aside, there are additional benefits to the introduction of electric propulsion in atmospheric flight: reduced noise levels, especially during approach to a large airport, increased reliability of aircraft, which means higher safety of passenger flight, and the insensitivity of electric motor operating performance from the flight conditions (altitude), with reduced operating costs of aircraft fleets.

On the other hand, the completed simulations proved that a simple replacement of the turbopropeller engines on a Dornier 328 regional commercial airplane with electric motors and batteries with an energy density of 180 Wh/kg while retaining the resultant mass of the aircraft would reduce its flight range from 1200 km to just a little over 200 km [2]. To restore the original flight range of 1200 km, all of the following modifications would have to be made:

- Reduce the aerodynamic drag by 20%,
- Increase the wing span by 50% to reduce the induced drag,
- Reduce the structural mass of the aircraft by 20%,
- Increase the battery energy density to 500 Wh/kg.

The application of electric propulsion without any other modifications to the existing aircraft designs would drastically reduce the flight range (by approximately 6 times) as of today.

Electric aircraft are not a new concept. In reality, the first flight of an electric-propulsion craft happened 20 years before the Wright brothers. In 1883, the French brothers Gaston and Albert Tissandier installed a 1.1 kW (1.5 HP) Siemens electric motor in an airship. Powered by dichromate battery cells, the motor developed an airspeed of 7 mph during a flight more than one hour long. The first manned flight in a fully electric aircraft took place in 1973, when Fred Militky outfitted an Austrian-made, Brditschk-developed HB-3 powered glider with a Bosch KM77 motor rated at 8-10 kW (11-13 HP). The maiden flight of the craft on 23/10/1973 lasted 9 minutes. This design was the first full-scale manned airplane powered purely with electricity. The subsequent flights, up to 12 minutes long and up to 380 m (1247 ft) of altitude, were limited by the capacity of the aircraft's batteries.

Another milestone was achieved in 1979 by the Mauro Solar Riser, which made its maiden manned flight as a solar-powered electric aircraft. In the same year, Bryan Allan succeeded in crossing the English Channel (the La Manche) in a Gossamer Albatross powered by PV panels. However, the most spectacular adventure involving electric aircraft was the flight around the globe accomplished by the Solar Impulse II in 2016 (fig. 2).

Fig. 2. Solar Impulse 2 shown on the tarmac Payerne Air Base, November 2014 [9]

Currently, the area of electric energy applications in aviation features two distinct and separate trends: "More Electric Aircraft", which is an evolutionary increase of electric power for onboard actuators, which have traditionally been hydraulic or pneumatic; the second trend has been gathering momentum for a few years now and is geared as a revolution to apply electric motors as the main or booster propulsion units in aircraft.

Further in this paper, the causes for the resumption of the development of electric aircraft propulsion are discussed with the barriers impeding the work, the technological conclusions from the applications of electric aircraft propulsion solutions, and the main directions of today's research.

2. Electric propulsion system

In the briefest terms, an electric propulsion system comprises four basic components which are interconnected to facilitate control over the flow of energy: the electric power source, the control module, the electric motor, and the fan or propeller, which converts the kinetic energy of the motor's rotor into aerodynamic thrust.

There are currently 3 versions of electric propulsion architecture being considered for aircraft [2]:

- Hybrid-electric,
- Turbo-electric,
- All-electric.

The hybrid-electric architecture is a combination of a traditional turboprop engine either with an electric motor powered by batteries (fig. 3) in a ‘parallel hybrid configuration’, or with an electric motor powered directly from batteries or voltage generators, which are in turn propelled mechanically via the turbine shaft. Given the location of the voltage generators in the layout, this is called a ‘series hybrid configuration’.

In both configurations, the turbofan is the main source of thrust for most of the flight duration. The limited electrical capacity of batteries means that electric booster motors are operated only when the thrust demand is peak (during take-off and climbing) or in cruise flight, when minimum thrust is required only.

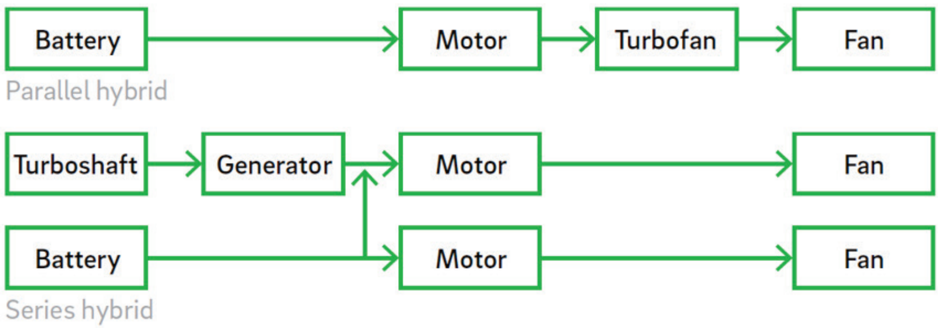

Fig. 3. Diagram of the hybrid-electric architecture [2]

The second version is **the turbo-electric architecture** which has the electric motors as the only source of aircraft thrust (fig. 4). In this configuration, a turbine engine is the source of kinetic energy for the turbine shaft, which propels an electric generator to produce electrical power for one or more fans, each driven by a separate electric motor. This configuration provides aircraft designers with much freedom in specifying the number and location of the fans/propellers, potentially leading to more efficient aircraft designs with a higher performance of propulsion systems.

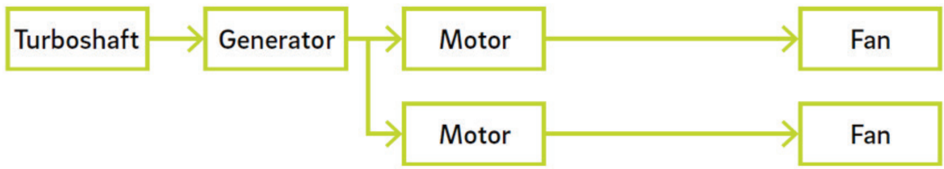

Fig. 4. Diagram of the turbo-electric architecture [2]

The third configuration version is all-electric propulsion with a battery being the sole power supply for the aircraft thrust (fig. 5). It is the only configuration which eliminates any need for a turbine engine and its fuel delivery system (which are present in the hybrid-electric and the turbo-electric architecture). It is obvious that the flight range of an all-electric propulsion aircraft will be highly dependent on the electrical capacity of batteries and the tare weight of the whole system.

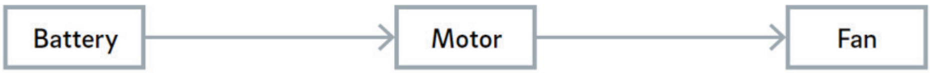

Fig. 5. Diagram of the all-electric architecture [2]

The presented versions of electric aircraft propulsion architectures are similar to those already applied by the automotive industry, the path of which is followed by the aerospace sector in many ways.

3. Sources of electric energy

As said before, the critical component of electric aircraft propulsion is the electrical energy generating and storage units. Current considerations focus on onboard electrical power generation by hybrid propulsion units, photovoltaic (PV) modules, and fuel cells. The two mainstream technologies of electrical energy storage and delivery units include batteries and supercapacitors.

Battery-powered aircraft can provide a very high overall efficiency of energy transfer flows – at more than 70% – compared to the modern efficiency of combustion propulsion systems, which achieve less than 40% with turbofan or turboprop engines. Battery-powered aircraft have the advantages of zero emissions, low costs of servicing, and no centre of gravity shifts during flight. Currently, the primary drawbacks of battery-powered propulsion systems include: shorter flight range with a relatively high mass (which is not reduced between take-off and landing), and the issues with electric battery recycling [4].

Specific power is the key performance metric, and the power output capacity per one kilogram of the power generator or the power storage (expressed in W/kg) energy density is the amount of electrical energy stored in a cubic metre of a unit (Wh/m^3). Specific energy is the amount of energy stored per one kilogram of the storage unit (Wh/kg). An electric energy storage system for aerospace applications must provide a minimum energy density (specific energy) of 500 Wh/kg or higher. The highest energy density of currently available batteries ranges from 150 to 250 Wh/kg, and Tesla's 21-70 battery with an advertised energy density within 250-320 Wh/kg unquestionably outperforms in the category. Analysis suggests that the current development pipeline of lithium-ion batteries (fig. 6) will achieve a gravimetric energy density of approximately 400-450 Wh/kg in 2 or 3 years. However, further evolution of electrochemical batteries or their potentially new, future technology will have to achieve 500 Wh/kg; even if this happens, it will still be 25 times lower than the energy density of liquid fuels and 50 times lower than the energy density of hydrogen.

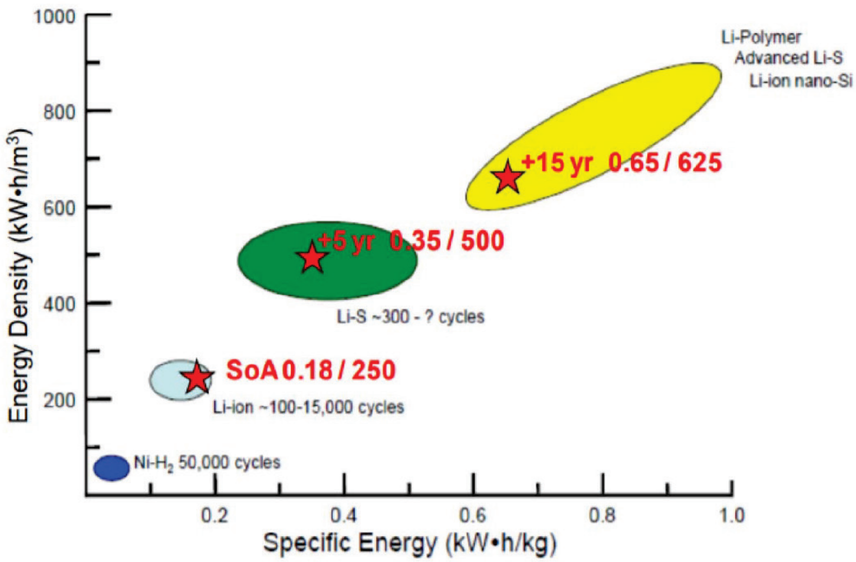

Fig. 6. Trend of energy density vs. specific energy change [17]

Batteries can achieve high levels of specific energy, but their specific power is generally low. A battery can store considerable levels of energy, but given the rate of its conversion from the chemical form into the electric form, the energy output rate, is slow, which may make a battery like this feasible in an electric aircraft to provide the flight range, but not acceleration of the craft.

A power supply unit can have the performance optimised by applying two different battery types: one with a high specific power and a second one with a high specific energy (fig. 7).

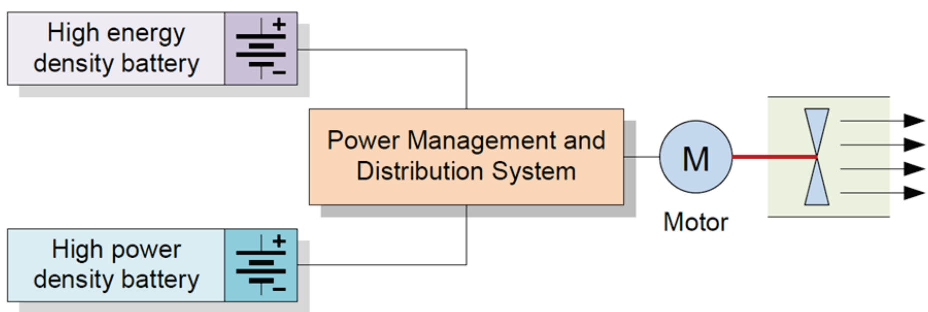

Fig. 7. Diagram of a power supply system with high specific energy and power [4]

The ratio of the specific energy to the specific power of a power source is a very important benchmark for comparison between different technologies. This ratio is often shown on a Ragone plot (fig. 8).

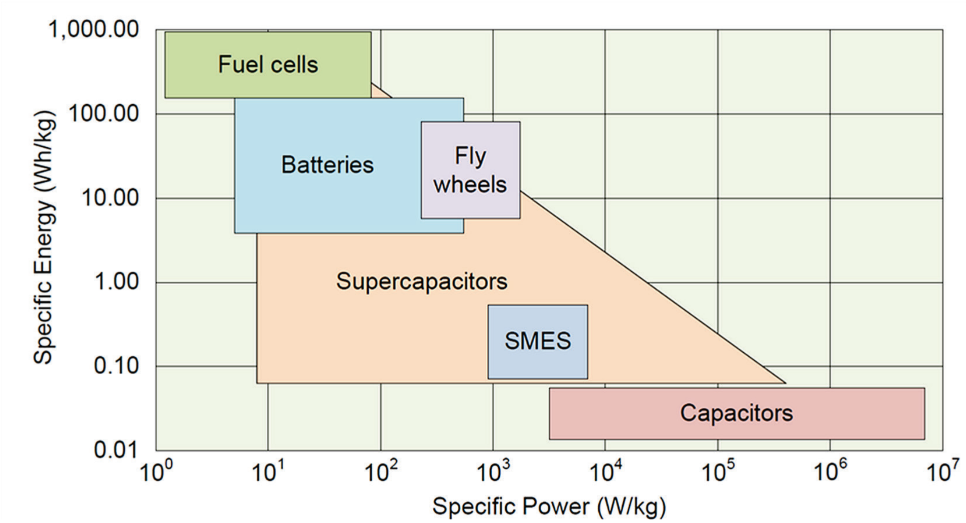

Fig. 8. Ragone plot [4]

To date, the following batteries have found applications in aviation [4]: lead-acid batteries in GA (general aviation) and light airplanes; nickel-cadmium batteries in large airplanes and helicopters; and lithium-ion batteries in large MEAs (More Electric Aircraft), like the Boeing 787 Dreamliner and all electric aircraft, including the Airbus E-Fan, which features the ICR 18650 Li-ion battery with 207 Wh/kg of specific cell energy and total available energy of 29 kWh from a 167 kg battery, which lasts for 1 hour plus 30 minutes of reserve. However, metal-air batteries are considered the future.

The interest in metal-air electrochemical cells is now growing because of their outstanding energy density compared to other battery technologies. The metal-air technology is not like Li-ion cells because they cannot be recharged by reversing the current flow, and the metallic electrodes are irreversibly altered by the electrochemical process, requiring replacement and reprocessing once they are spent. For the aircraft operators, the necessary replacement of metal-air cells could be compared to the necessary of refuelling before each flight.

A distinct quality of metal-air batteries compared to traditional electrochemical batteries is the ambient air-breathing electrode which is required to power the active cathode material (which is oxygen). Metal-air cells can be manufactured from different materials for the metal electrodes, including Li, Zn, Al, Na, Mg, Ca, or Fe and require an electrolyte capable of conducting metal ions. The electrical energy is generated in a metal-air cell by reduction and oxidation occurring between the metal and oxygen.

Supercapacitors, also called 'ultracapacitors' can generate much higher levels of specific power (multiple kW/kg) while enjoying lower specific energy capacity (which is currently a few Wh/kg) when compared to batteries [4]. The structure of a battery system is a compromise between specific energy and specific power, while supercapacitors might satisfy the demand for peak power in a relatively short time. The division of power of batteries/supercapacitors done in this way is the basic operating principle of Hybrid Energy Storage Systems (HESS) and the primary factor which affects the size and service life specification of battery systems. The highest power demand occurs during take-off and climb, naturally.

The most common supercapacitor type is electric double-layer capacitors (EDLC), which store electrical energy in an electrostatic field. EDLCs have a very long service life, capable of operating for millions of charge/discharge cycles, and feature relatively fast charge and discharge rates when compared to batteries. An application example of EDLCs includes the fuel-saving IC engine start-stop systems of modern road vehicles. There are environmental benefits of supercapacitor applications, as their manufacture does not need precious materials, like lithium or cobalt, which may help to avoid the issues of flammability and toxicity of the metals.

Supercapacitors are a reliable alternative to Li-ion battery cells and their development is enjoying growing interest of national and industrial organisations. Nevertheless, novel types of hybrid supercapacitors based on the established Li-ion technology are being developed today. The NASA Kennedy Space Center is researching the development of ultracapacitors based on graphene, which utilise the large available surface area of the material (2,600 m^2/g) to increase the storage capacity for electrical energy. The latest news in the media suggest that the development of aqueous supercapacitors by Superdielectrics Ltd. might soon help to achieve up to 180 Wh/kg of energy density.

Fuel cells (FC) resemble electric batteries in that they output electrical energy from a chemical reaction. The chemicals most commonly used in FCs include hydrogen and oxygen, although certain FCs operate on methane or methanol. The primary difference in the operation of FCs in comparison to combustion engines is that the chemical energy of an FC is released as electric current and not heat, due to which fuel cells provide high energy efficiency with low emission levels [4]. Fuel cells achieve higher specific energy levels than Li-ion batteries, up to 1980 kJ/kg (550 Wh/kg). On the other hand, the energy output rate (or specific power) is lower in FCs. Hence, an FC system for aircraft necessitates a hybrid approach to satisfy the peak power demand, especially during take-off and climb. Fuel cells also require onboard storage of pressurised hydrogen and intake of air in flight. These are the limiting factors for potential FC applications in aircraft.

Energy recovery systems can provide optimised energy usage in aircraft during ground and flight operations. Tests performed on UAVs (unmanned aerial vehicles) designed for high-altitude long flight demonstrated the capabilities which result from the addition of fuel cell regeneration technologies, which operate by PV panels during the day to replenish the onboard reserves of hydrogen and oxygen. Tests were also performed to examine the efficiency of electric regenerators wired to electromechanical actuators in aircraft. In 2007, Delos Aerospace patented an all-electric landing gear system named KERS (Kinetic Energy Recovery System), which recovered the kinetic energy from aircraft braking on the ground for later use in propulsion of the landing gear wheels during taxiing and take-off, to reduce the minimum required runway length and help to reduce noise [4].

Photovoltaics (PV): The modern photovoltaic technologies began evolving with the silicon PV cells developed in the USA in as early as 1954; by 1964, NASA launched the Nimbus satellite into space, a device powered by a 470-watt PV panel. Ten years later, the first PV-powered airplane (the Sunrise 1) was launched from a 12-kg MTOM, carried 4096 PV cells with an efficiency of 11% and generated 450 W of onboard power. An important performance parameter of PV cells is their efficiency of solar energy conversion, usually expressed as the percentage of generated electrical energy to the solar energy of irradiation.

Currently, many different photovoltaic technologies exist and include silicon cells, organic cells, polymer cells, hybrid PV cells, and thin-layer solar cells, achieving efficiency that can reach 44%. However, the structure and cost-efficiency of silicon PV cells make them the only ones deemed suitable for solar-power aircraft. The PV cells can be made with mono-crystalline, poly-crystalline or amorphous silicon with an approximate efficiency of 16-22%. SunPower recently delivered the 22,000 PV cells that were installed in the wings and the tail plane of the Solar Impulse aircraft. Each PV cell was only 135 micron thick with an approximate efficiency of 22.7% [4].

Superconducting Magnetic Energy Storage (SMES) is a method of storing electrical energy through generating and sustaining a magnetic field. When electric current flows through a cryogenically-cooled superconducting winding, it will continue to flow even with the voltage input removed from the terminals. This is how the magnetic field can be sustained, as the line resistance is negligible. SMES demonstrates high response and efficiency (with more than 95% for charging and discharging). It makes SMES most suitable for high power, short-cycle applications [6]. SMES coils are usually made of niobium and titanium (NbTi), with a critical temperature of approximately 9 Kelvins. There is progress in the engineering of superconductor materials, especially in increasing the critical temperature; the point at which the superconduction transfer occurs. Provided the progress in material engineering is sufficient, SMES are considered as viable future replacements for electric batteries [4].

The foregoing technological barriers extend the time to achieve commercial profitability of electric and electric-hybrid propulsion systems in commercial passenger airliners. Nevertheless, the development of new technologies now witnessed in electric propulsion makes one hopeful that the barriers can be overcome soon.

4. Electric motors and their control systems

Although the operation of the electric motor is based on common principles of electromagnetism, the motors may vary greatly in their starting and control methods. Currently, more than 100 types of electric motors are classified. The four main types of electric motors used in EVs (electric vehicles) include induction motors, brush direct-current motors, BLDCs (brushless direct-current motors) with permanent magnets, and switched reluctance motors (SRM). Among these four types, BLDCs and SRMs are considered today to be most suitable for aircraft propulsion because of their high specific power and reliability in comparison to induction or brush DC motors.

Both SRMs and BLDCs are simple, durable, and compact synchronous machines which do not need electrical current to be supplied to the rotors. Their operation, however, requires complex control circuitry based on pre-programmed microchips and solid-state (electronic semiconductor) switching. Among the existing types of electronic switches, IGBTs (insulated gate bipolar transistors) are the preferred choice for high-voltage propulsion systems with current levels in excess of 50 A, which are typical of those required for aircraft.

The tests intended to increase the power density and efficiency of electric motors in aviation applications include axial magnetic field motors coupled with HTS (high-temperature superconductors) and constrained magnetic flux. The theoretical test results confirmed this type of motor may reach an efficiency of 99%.

The E-811 motor developed by Pipistrel (fig. 9) is the world's first electric motor certified 6 (Cert. No. EASA.E.234) for general aviation by the European Union Aviation Safety Agency (EASA).

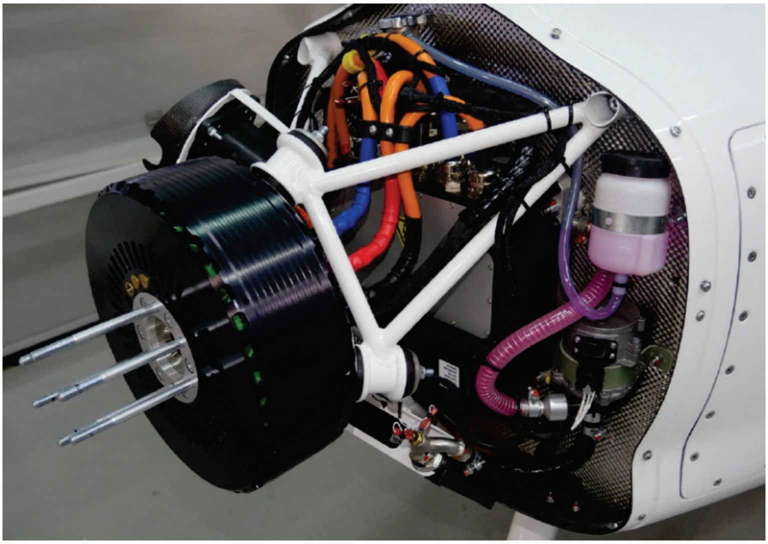

Fig. 9. E-811 motor installed onboard the Pipistrel Velis Electro [10]

The propulsion system combines an electric motor and an electronic power controller, both of which are liquid-cooled. Providing 57.6 kW (77 HP) of peak power and 49.2 kW (66 HP) of continuous maximum power, the E-811 is a perfect motor for powered gliders, UL aircraft, LSAs, and VLAs, which require type-certified propulsion. It can be installed on Part-23 Level 1 aircraft and other distributed propulsion configurations. The motor measures 26.8 cm in diameter and 9.1 cm in length with a weight of 22.7 kg.

The E-811 is a modern BLDC with permanent magnets on the rotor and axial magnetic flux. Thanks to these features, the relatively compact construction of the motor delivers higher power than traditional, radially spinning magnetic field motors. The propeller is installed directly on the motor output shaft.

The power controller converts the DC (direct current) of the batteries into AC (alternating current) for the motor power input. The power controller selects the command signals over a CAN bus from the pilot who operates the control levers in the cockpit and responds by modulating the motor input AC frequency and level on the high-current AC power supply bus. The motor's direction of rotation is not factory-determined and can be easily converted for any application of the installation.

The E-811 is compatible with a wide selection of propellers, both with fixed or electrically variable pitch, with the only constraint being the propeller flange geometry and the bolt patter (6xM8 over 75 mm dia.). The maximum moment of inertia of the propeller must be 3245 kg-cm^2 (7.7 lb-ft^2) and the maximum propeller weight must be 5.5 kg. The motor's maximum speed is 2500 rpm.

Fig. 10. YASA-750R motor of the Rolls-Royce "Spirit of Innovation" [11]

The YASA 750R (fig. 10) is a BLDC [8] with permanent magnets on the rotor and axial magnetic flux, capable of developing high torque. The maximum torque rating is 790 Nm with 200 kW of peak power within the controlled speed range of 0 to 3250 rpm. The motor measures 36 cm in diameter and 9.2 cm in length with a weight of 37 kg. This means a peak power density of more than 5 kW/kg. The mechanical design of the motor makes installation and integration easy, providing the propulsion unit with sufficient strength and rigidity. Three YASA-750R motors connected in series (Fig. 9) were installed to drive the three-blade propeller onboard of the Rolls-Royce "Spirit of Innovation" airplane. It took its maiden flight on 15/09/2021.

5. Implemented projects and research

Currently, there is research into aerospace applications of electric propulsion carried out at 70 research centres and design engineering units. Many of them are third-party operations which had were related to aviation.

The most advanced work, some of which were finished with certification and project implementation, concern small aircraft for GA and air taxis. The work on the application of alternative aircraft propulsion systems (which include electric power) in commercial aviation is primarily led by the design offices of the largest aerospace organisations, such as NASA, Airbus, Boeing, Cessna, Rolls-Royce, and Agusta Westland [6].

So far, the first and the only all-electric airplane certified by the EASA in 2020 is a 2-seater trainer, the Velis Electro (fig. 11) designed and built by Pipistrel of Slovenia.

Fig. 11. Velis Electro all-electric airplane [12]

The Velis enjoys 1:15 of L/D (lift/drag ratio). The factory-made Pipistrel E811 helps the craft to develop a cruise speed of 160 km/h, while the batteries provide 50 minutes of service flight plus a reserve. With this performance and the low operating costs, the aircraft is perfect for circular flight training.

Fig. 12. NASA X57 Maxwell electric airplane [13]

An interesting version of an electric propulsion airplane has been developed and tested by NASA, with an application of propulsion thrust distribution. This project has the codename "X57 Maxwell" (fig. 12). The aircraft features a distributed electric propulsion system, comprising 14 motors installed along the leading edges of the wings. Twelve of the smaller, separately propelled fixed-pitch propellers are only operated at small flight speeds to overcome drag. In cruise flight, the small propellers – which boost the take-off and climbing thrust – are folded away along the nacelles, and the main propulsion is provided by the two motors on the wing tips. The larger and more powerful cruise-flight propellers installed there provides favourable swirl interactions and may reduce drag by up to 5%. The performance of this craft is 100 miles of flight range at 172 mph or cruise speed, which position the Maxwell as an air taxi with astonishingly low operating costs.

Another prototype of an all-electric air taxi is the Lilium Jet VTOL (fig. 13). The futuristic lines of the Lilium stem from an aerodynamic optimisation of the airframe to fully utilise the potential of electric propulsion.

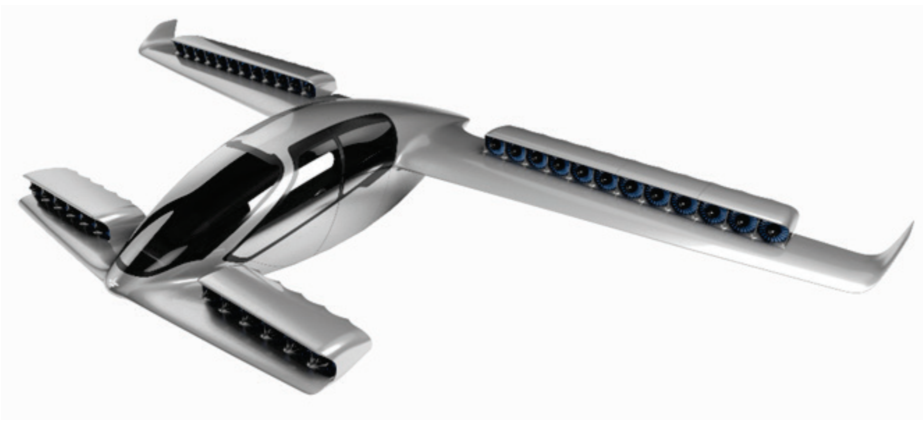

Fig. 13. Lilium Jet VTOL [14]

The Lilium is designed as a seven-seater air taxi capable of vertical take-off and landing. The distributed propulsion of this aircraft is formed by 36 electric motors installed over the aft part of the airfoil and capable of tilting by 90 degrees from the centreline with thrust vectoring. This design helps to apply electric propulsion both for the generation of thrust and extremely efficient attitude control. The project provides for the aircraft being capable of flight operations up to 3,000 m of altitude with a cruise speed of 280 km/h. The manufacturer intends to have the plane certified in 2 to 3 years.

On 15/09/2021, the maiden flight was made by Rolls-Royce's all-electric airplane, "Spirit of Innovation" (fig. 14). The craft is propelled by three light-weight YASA-750R electric motors, driving a single, three-bladed propeller in a conventional performance form.

Fig. 14. Rolls-Royce "Spirit of Innovation" all-electric airplane [15]

Weighing 82 pounds (37 kg) each, the YASA-750R motors develop more than 500 horsepower together for the variable-pitch propeller. This helps to optimise the application of motor torque and speed in flight. These axial magnetic flux motors enjoy a high power density and run at lower speeds than traditional combustion engines, which improves flight stability and reduces noise. The power source for the craft is a bank of 6000 high energy density power cells, making the aircraft capable of flight from London to Paris (200 miles) on a single charge. Here, given the sheer power level, cooling the propulsion system is a major challenge. The 6000 battery cells are densely packed ahead of the cockpit and require heavy-duty cooling. Liquid cooling is applied which extracts the heat to the radiators installed on the fuselage surface (and made barely noticeable). With a propulsion system efficiency above 90%, only 75 kW (100 HP) of the power output is expected to be lost as heat. The aircraft has been built to break the speed record of an all-electric airplane, which is currently 213 mph (343 km/h) and held since 2017 by the electric-propulsion-converted Extra 300 acrobatic airplane from Siemens. The Spirit of Innovation is planned to achieve 300 mph of maximum speed.

For commercial airliners, which are airplanes intended for carrying many passengers over a long distance, various alternatives to traditional combustion engines are considered, including hybrid-electric propulsion systems, the application of fuel cells to supply electrical energy in flight, and hydrogen as a replacement of liquid aircraft fuel. The leading corporations which are working on CO_2 emission reduction with conversion for electric aircraft propulsion include Airbus with its ZEROe project (fig. 15), ZeroAvia with the HyFlyer, and Boeing [2, 6].

Fig. 15. Airbus ZEROe hybrid-electric airplane [16]

Aside from the aircraft which have already been certified or have seen their first flight, advanced work is under way across the world and on many other projects which involve applications of electric aircraft propulsion.

6. Conclusions

50 or 60 years ago, it was the general consensus that electric propulsion was not viable for aircraft. It seemed that no electric motor was capable of producing the amount of power required to generate enough lift to offset the total weight of the craft, its pilot, the electric motor, and the batteries necessary to supply power to the propulsion system. Technological advancement has forced everyone to revisit the consensus.

Despite the distinct progress in the work on electric aircraft propulsion, many barriers remain to be overcome; an example to illustrate this is the propulsion system diagram shown in fig. 16. The primary barriers are the market demand for electric airplanes, which varies with the aerospace sub-sectors, and the technological and legal obstacles. The technological obstacles in the current phase of electric aircraft development are twofold: the barriers directly related to the electric propulsion systems and the barriers to the planned applications of the aircraft which are now in development. High capacity and low weight of electric batteries are key to the delivery of all-electric and hybrid-electric propulsion architectures, as well as to launch the production of propulsion that provides a commercially profitable range and payload capabilities. High charging speeds and extension of battery service life will be critical to future development of battery-powered airplanes.

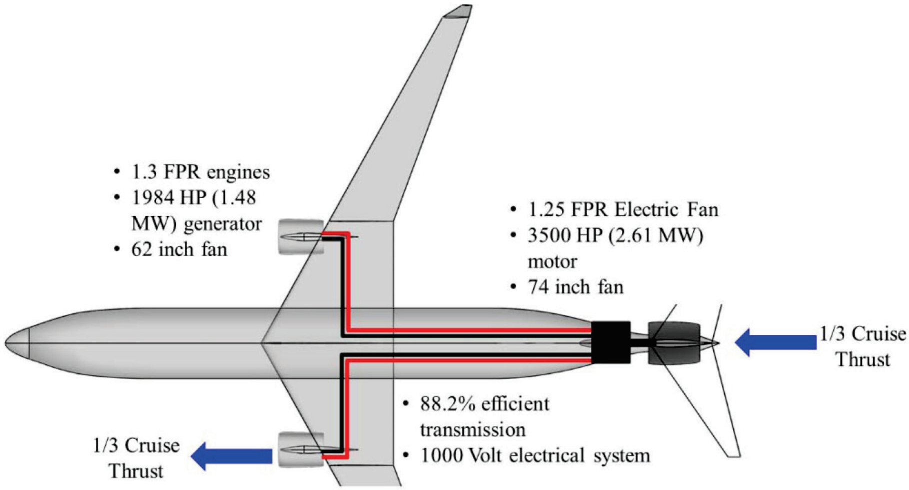

Fig. 16. Airplane configuration with the propulsion unit in the tail section and the postulated design of the propulsion and energy supply systems [17]

The safety of electric batteries is a considerable issue, an example of which is the failure of the Li-ion batteries aboard the Boeing 787 from several years ago. Electric aircraft design engineers will have to develop efficient hazard containment systems for high energy density batteries not only to satisfy the flight worthiness criteria but also to assuage the fears for public safety. While the thermal hazard containment provided by battery sealing systems is less of a challenge than thermal hazard containment for liquid aviation fuels, the necessity of the containment for electric batteries must not be dismissed in the technological race for higher levels of energy density. This factor becomes especially important when considering the power engineering systems of many megawatts required by regional and larger commercial aircraft, and the resulting need for expelling all generated surplus heat.

It seems then that the greatest interest in electric aircraft at its first stage of evolution will come from general aviation, with applications in flight training and pleasure flights, urban air taxis, and potentially, regional and business aircraft.

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7. References

1. Balicki W., Chachurski R., Głowacki P., Godzimirski J., Kawalec K., Kozakiewicz A., Pągowski Z., Rowiński A., Szczeciński J, Szczeciński S.: Lotnicze silniki turbinowe. Konstrukcja – eksploatacja – diagnostyka, cz. 1. Instytut Lotnictwa, Warszawa 2011.
2. Berger R.: Aircraft Electrical Propulsion – The Next Chapter of Aviation?, www.rolandberger.com, 2017.
3. Białecki T., Dzięgielewski W., Kowalski M., Kulczycki A.: Reactivity Model as a Tool to Compare the Combustion Process in Aviation Turbine Engines Powered by Synthetic Fuels. MDPI, Energies, Vol. 14, 2021, DOI 10.3390/en14196302.
4. Bolam R.C., Vagapov Y., Anuchin A.: Review of Electrically Powered Propulsion for Aircraft. 53rd International Universities Power Engineering Conference (UPEC), 2018.
5. Bowman C.L., Felder J.L., Marien T.V.: Hybrid Propulsion Systems for Remotely Piloted Aircraft Systems. AIAA Propulsion and Energy Forum, Cincinnati, Ohio, July 9-11, 2018.
6. https://www.electricfuture.com/electric-planes-the-current-state-of-electric-aircraft/
7. https://www.easa.europa.eu/sites/default/files/dfu/E.234%20TCDS%20Pipistrel%20electric%20engine%20E-811_Issue%2001.pdf: EASA Type-certificate for Pipistrel E-811 Engine
8. https://www.yasa.com/wp-content/uploads/2021/05/YASA-750RDatasheet-Rev-11.pdf
9. https://en.wikipedia.org/wiki/Solar_Impulse
10. https://www.pipistrel-aircraft.com/aircraft/electric-flight/e-811/
11. https://www.yasa.com/products/yasa-750/
12. https://geekweek.interia.pl/lotnictwo/news-oto-pipistrel-velis-electro-czyli-elektryczny-pogromca-lotni,nId,5546352
13. https://sacd.larc.nasa.gov/x57maxwell/
14. https://www.aerotime.aero/18456-video-first-flight-of-lilium-5-seater-vtol-aircraft
15. https://simpleflying.com/rolls-royce-all-electric-flight/
16. https://www.fly4free.pl/airbus-pokazal-zeroe-czyli-samoloty-przyszlosci-rewolucyjne-zmiany-juz-za-kilka-lat/
17. Wheeler P., Sirimanna T.S., Bozhko S., Haran K.S.: Electric/Hybrid-Electric Aircraft Propulsion Systems. Proceedings of The IEEE, Vol. 109, No. 6, June 2021.