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Electric energy use in aviation, perspective, and applications

Havacılıkta elektrik enerjisi kullanımı, perspektif ve uygulamalar

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Electric Energy Use in Aviation, Perspective, and Applications

Highlights

- *Electric energy use in aircraft propulsion and systems provide a means of emission and cost-effectiveness.*
- *Historically electric energy use is made possible only after achieving advancements in electric motors and batteries.*
- *Because of the current state of technology and cost considerations, a system-wide approach and mission-specific system design seems a necessity for further electrification of aviation*

Graphical Abstract

Electric energy use in civil aircraft is increasing due to several factors such as environmental responsibility, maintenance and operations cost savings, and efficiency. This paper presents the key technological changes that made it possible to use electric energy in aircraft propulsion and systems and discusses the future requirements for further electrification of aviation.

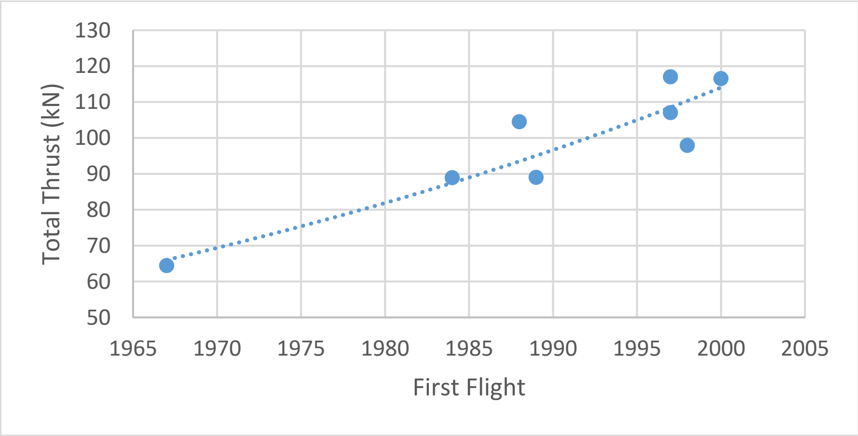

Figure. Power trend in Boeing737 series aircraft

Aim

This paper presents the key technological changes that made it possible to use electric energy in aircraft propulsion and systems and discusses the future requirements for further electrification of aviation.

Design & Methodology

Historical advancements of technology are analyzed to figure out the fundamentals of today's applications which is used as a baseline for the determination of future requirements set for more electric energy use in civil aviation.

Originality

In aviation, electric use has some technical bottlenecks which have to be solved before employing in a wider context. This paper discusses the requirements for future electric use by analyzing the current applications.

Findings

Electric energy seems like a promising technical advancement for increasing environmental and cost efficiency and is getting wider use in civil aviation.

Conclusion

Further electrification of aviation is dependent on overcoming some fundamental technological areas such as battery capacity, electric motor weights, and electrical control systems.

Declaration of Ethical Standards

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Electric Energy Use in Aviation, Perspective, and Applications

Derleme Makalesi / Review Article

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ABSTRACT

The electric aircraft concept is recently gaining interest in the industry, due to environmental and economic reasons. Recent research shows that More Electric Aircraft applications may provide around a 20% decrease in CO_2 and NOx emissions, a 50% decrease in noise, and a 20% reduction in fuel consumption compared to the previous conventional version of the same aircraft manufacturer. Considering that civil aviation is responsible for over 2% of all man-made emissions, any improvement is important in this area. Electric power seems an important player in achieving the goals of reducing emissions. This paper reviews the trend of electric energy use in aviation and the development of the definition of electric aircraft in the literature. It is seen that electric energy use is gaining great interest parallel to the achievements in electric energy storage and management. This paper presents the key technological changes that made it possible to use electric energy in aircraft propulsion and systems and discusses the future challenges for further electrification of aviation.

Keywords: Aircraft propulsion, electric aircraft, more electric aircraft, aviation.

Havacılıkta Elektrik Enerjisi Kullanımı, Perspektif ve Uygulamalar

ÖZ

Elektrikli uçak konsepti, çevresel ve ekonomik nedenlerle son zamanlarda sanayide ilgi görmektedir. Yakın zamanda yapılan araştırmalar, Daha Fazla Elektrikli Uçak uygulamasının, aynı uçak üreticisinin önceki konvansiyonel modeline kıyasla emisyonlarda yaklaşık %20, gürültüde %50 ve yakıt tüketimlerinde %20 azalma sağlayabileceğini göstermektedir. Sivil havacılığın tüm insan kaynaklı emisyonların %2'sinden fazlasından sorumlu olduğu düşünüldüğünde, bu alandaki her iyileştirme önemlidir. Elektrik, emisyonları azaltma hedeflerine ulaşmada önemli bir etken olarak görünmektedir. Bu makalede, havacılıkta elektrik enerjisi kullanım eğilimi ve literatürde elektrikli uçak tanımının gelişimi ele alınmıştır. Elektrik enerjisi depolama ve yönetimi alanındaki kazanımlara paralel olarak elektrik enerjisi kullanımının da büyük ilgi gördüğü görülmektedir. Bu makale, elektrik enerjisinin uçak tahrik ve sistemlerinde kullanılmasını mümkün kılan temel teknolojik gelişmeleri sunmakta ve havacılığın daha fazla elektrifikasyonu için gelecekteki zorlukları tartışmaktadır.

Anahtar kelimeler: Uçak tahriki, elektrikli uçak, daha elektrikli uçak, havacılık.

1. INTRODUCTION

Although before the 1900s, the first automobiles had all-electric powertrains, following the Ford Industrial revolution, automobiles became using internal combustion engines (ICE), which made them cheaper and widely available. At the beginning of the 1900s ICE engines were lighter and cheaper compared to the electric alternative. This affected the aeronautical history which started at those years, for selecting the ICE engine as a primary power source.

Early aircrafts flight mechanisms were powered manually, using rudder pedals and a stick which were connected to aerodynamic surfaces by wire ropes (fly-by-cable). In the 1940s, some aircraft became so heavy which arose the need of adding hydraulic power to move the aerodynamic surfaces. In the late 1950s, hydraulic power started to be used alone. Later in the 1970s fly-by-wire was used first in F-16 (1975), Mirage (1980), and later on Grippen (1988). In the full fly-by-wire system, electric signals from the controls make a computer system activate the control surfaces. This system had no mechanical means of backup [1].

Research for electric and hybrid propulsion systems has been a general concern for industry for a long time [2]. The concept of electric actuation in aircraft is first proposed in 1916 [3]. Following the technical developments on electric energy storage and handling, More Electric Aircraft (MEA) concept is studied and further developed [4]–[8]. Following WWII, the power need for complex subsystems gained more interest where several design solutions for powering even primary flight controls were developed [9].

In the 1970s, all-electric studies started [5] with the first electric aircraft Militky MB-E1 which made its first flight on 23 October 1973 lasting 12 minutes with Ni-Cd

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batteries [10]. With similar experiments of all-electric aircraft, a more electric concept seemed as a mid-term solution for the emerging power need of aviation.

1.1. MEA Concept

Although this concept is nearly a hundred years old, the development of power electronics and electric machine production techniques, made way to the renewal of interest in MEA [11], [12]. Besides the technological advances of components, environmental challenges have become a primary concern.

NASA has set targets for the industry that in 2020, compared to 1998, 50% less fuel consumption, 75% less NOx emission, and 42 dB less noise shall be achieved [13]. Similarly, European Union set forth ambitious targets for reducing the emissions in Flight Path 2050 [14] with the goals of 75% reduction in CO_2 and 90% less NOx.

Pearson [15] listed the advantages of MEA in 1998 as the followings;

- Up to 6.5% decrease in take-off gross weight.
- Up to 3.2% decrease in life cycle cost.
- Up to 5.4% increase in Mean Time Between Failure (MTBF).
- Up to 4.2% decrease in 'maintenance man-hours per flying hour'

Recent developments in the power electronics industry, lead to more efficient and economic electric machines and actuators. This created an opportunity for MEA, to remove mechanical, pneumatic, and hydraulic power transmissions and establish electric distribution and actuation instead. In this way, weight decrease is gained which also leads to fuel economy, low emissions, and low noise. Research made by NASA showed that usage of more electric technologies will provide a 10% decrease in empty weight, 13% decrease in required engine power, 20% decrease CO_2 and NO_X emissions in and 9% decrease in fuel consumption for a typical 200 seater aircraft [16], [17].

In an MEA example, if Airbus A380 aircraft to use conventional power distributions, the total trust of approximately 40 MWs would be divided such as 200 kW electrical, 1,2 MW pneumatic, 240 kW hydraulic, and 100 kW of mechanical power which forms a total of 1,7 MWs "non-trust" power would be taken from the engines. Instead, using the MEA concept, 40 MW thrust of A380 engines provide 1 MW electric system power, and the rest 39 MW is used as thrust power. Additional advantages like removing bleeding air and mechanical connections also provide efficiency and weight improvements on the engine [18].

Following the first efforts in the 1980s, the MEA concept definition had found ground and literature and became an accepted definition.

Cronin [5] underlines that electric use in aviation offers the benefits of eliminating such labor-intensive systems as engine bleed air, high-pressure pneumatics, hydraulics, and the nonelectric engine-start systems. It is also determined as “ultra-reliable”, higher maintainability, less support equipment, and manpower, more survivable, higher in performance, and lower in cost [4], [8]. Electric aircraft term is defined as using electrical power for aircraft subsystems which are normally powered by hydraulic, pneumatic, or mechanical power, including flight control actuation, environmental control system, fuel pumps, and other utility functions [19]. In later years, electrification of the aircraft is defined as removing the need for on-engine generation of hydraulic power and bleed air, and the use of power electronics in the starter/generation system of the main engine [20].

Another aspect of having electric energy onboard is the removal of onboard mechanical and hydraulic energy transfer systems. McLoughlin gives a brief definition as electric vehicle networks are likely to support a number of electromagnetic machines that both provide electrical power to the network and use that power to perform a useful task [21]. Gandolfi et.al added a perspective on the propulsion side as electrification is the extension of engine life and economy [22].

Besides the benefits of electrification, there are also concerns that are concentrated on the maturity of power electronics [23] and the handling of regenerative electromagnetic loads [24]. Temperature considerations on power electronic systems are also discussed in the literature [13]. Efficient and more reliable ways need to be developed for electric power generation, conversion, and distribution is also discussed as another dimension of disadvantages of aircraft electrification [25].

It is also interesting to note that the defined challenges, changed in years. The developments on power electronics and electronic control systems, made it possible to be able to use electric energy onboard the aircraft. While in the first years, cost and reliability were the main focus, by time, it changed to be further utilization of electronic and software systems.

Another advantage which is referred to in literature is that MEA reduces the need and deployment of ground support equipment by around 20%, which is an important economical factor [8].

1.2. Electric Energy Storage

In each and every aeronautical vehicle, batteries are present as electrical energy storage regardless of the architecture and propulsion concept of the aircraft. Their main purposes are:

- to peak-shave (store and release) for electric loads in the DC system;

- to provide power in startup;
- to provide energy for emergency conditions.
- to provide energy for instant loads

In order to provide the above functionalities, generally, batteries of various technologies and electrochemistry are used. Battery selection for aeronautical applications depends on the requirements of the mission of the air vehicle. Applications such as Mars Landers, Moon Rovers, GEO Orbiters, LEO Orbiters, Aircrafts, UAVs all represent different requirements. Even in aircraft, requirements of the battery systems differ depending on the ceiling, electric loads, mission type, etc. of the aircraft. As an example, a long cycle time is required for satellite applications where a high discharge rate (power) can be the primary requirement for aircraft [26], [27].

While general focus is given to the electrical systems and their applications, battery and electric energy storage are being disregarded till the 2010s. An incident that takes place in 2013, showed that the main consideration in MEA is the energy storage system [28], [29]. As progress in electric propulsion in the automotive industry is faster, MEA is following the advances in this industry and its applications.

It is important to mention that safety considerations are crucial as performance. Accidents due to battery failure can take the aviation sector and electrification research many years backward. As it happened in 2013, where the Boeing company experienced technical and financial problems following a battery failure [28], [29]

The development of Electric and Hybrid Vehicles (EVs and HEVs) is helping to meet fuel economy and environmental regulations [30]. These technologies utilize Lithium-ion batteries for energy storage because it is the most advanced technology for batteries in its high specific energy, high voltage, and low self-discharge rate dimensions [31]. Therefore, it is important that the battery life is needed to be extended and their full capacity utilization is required.

Thermal management of batteries is critical for achieving the desired performance and the desired life of batteries safely. The heat generated inside a battery must be dissipated to improve reliability and prevent failure [32], [33]. Batteries degrade rapidly at temperatures outside the working envelope, while colder temperatures reduce performance capabilities [34], [35]. In battery utilization in transportation applications, a thermal management system is required to operate the batteries in the acceptable temperature range; and to minimize the temperature differences among the cells of the battery [32]. In a battery system, high-temperature differences could lower the performance of the battery and as a result, the performance of the system can be negatively affected [36].

Table 1 Aircraft model power specifications [37]

Aircraft Model	First Flight	Power (kN)
B737-100	1967	64.4
B737-300	1984	88.9
B737-400	1988	104.5
B737-500	1989	89
B737-600	1998	97.9
B737-700	1997	107
B737-800	1997	117
B737-900	2000	116.5

1.3. More Electric Aircraft Applications

Aircraft in service and their power utilization are given in Table 1 and in the graphic that shows the trend in *Figure 1*, it is seen that power demand in aviation is increasing within newer aircraft. The demand for electric power is also increasing due to advanced electronic systems used in avionics.

Back in 80's NASA supported studies on the all-electric aircraft (AEA) concept, after which some limited applications on civil and military aviation are developed. Following the results of 1980 studies, some of the results and subsystems were found technically feasible, but since the aerospace industry is conservative on reliability and certification issues, an alternative step towards keeping the current technology and using more electric solutions [9] which are then called more electric aircraft (MEA) concept was taken by the industry.

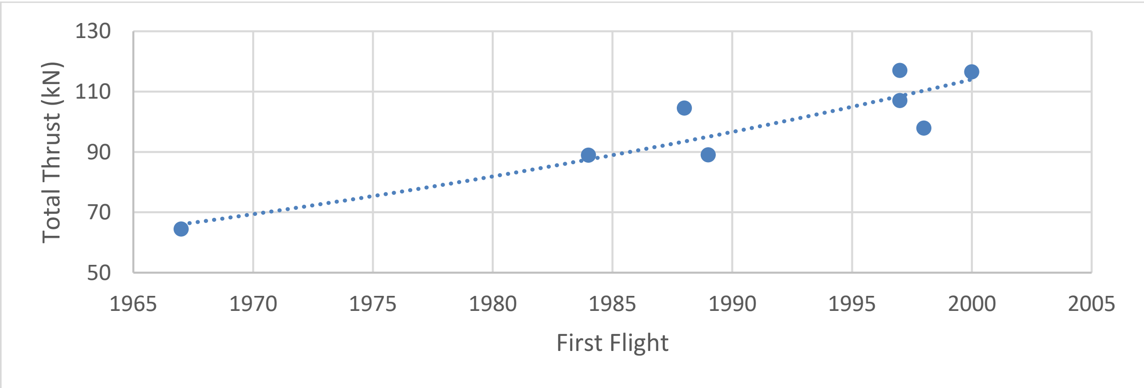

Figure 1 Power trend on Boeing 737 series aircraft

The current energy requirements of large aircraft are over the capability of the electric energy storage technologies. Therefore, using the aircraft engines as a generator for electric power is far more convenient for responding to the electric power demand of the aircraft.

1.4. All-Electric Aircraft

Research on electric aviation is still an interesting title for both the academic and aeronautical industries. The all-electric aircraft already on the market are provided in Table 2.

The aircrafts listed in Table 2 exhibit that for large civil aviation, the all-electric concept is fully dependent on the performance and capabilities of the batteries. Battery technology is showing great improvement by means of storage capacity and the main driving force for this development seems to be the automotive industry [38], [39].

400-600 Wh/kg for battery technologies in around 20 years' time frame, only hybrid and more electric concepts seem to be possible [46]. NASA defines batteries as a key technological area for further research on reports on technology roadmaps [47], [48]. On the other hand, battery costs have a trend to fall rapidly [49]

By adopting policies and required efforts to bring out the full potential of the lithium-ion batteries' role in energy sustainability can be achieved. The following actions are set forth in literature to be the key actions in fulfilling the above role [50]:

- reducing the carbon footprint
- developing effective means of battery recycling scheme
- minimizing dependencies on heavy minerals such as cobalt
- bringing down costs

Table 2 Electric aircraft and specifications [40]–[45]

Model	Maiden flight	OWE (kg)	MTOW (kg)	Motor Power (kW)	Range (km)	Seat	Battery Capacity (Wh)	The battery energy density (Wh/kg)	Battery type
Solar One	1979	104,3		3	1,2	1	720		NiCd
Lange Aviation Antares 20E	2003	475	660	42	220	1	10.627	136	Liion
Electravia BL1E Electra	2007			18	50	1	4.700		LiPo
Electravia Electro Trike	2008			19	100	1	3.000		LiPo
Pipistrel Taurus Electro	2009	306	450	40		2	6.500	155	Li-ion
Yuneec E430	2009	250	470	40	227	1	2.000	154	LiPo
EADS Cri-Cri	2010	78	175,5	22	200	1	500	18,7	LiPo
Alisport Silent 2	2011	205	315	22		1	4.300	277	LiPo
Airbus E-Fan	2014		550	60	200	2	29.000	174	LiPo
Pipistrel Alpha Electo	2014	377	550	50	200	2	17.000	135	Liion
Lange Aviation Antares 23E	2013	525	850	42	220	1	10.627	136	Li-ion

2. FUTURE PROSPECTS

Lithium batteries are one of the most successful products of technology. These batteries have already wide area of use in the consumer electronic market without any alternative solution. With the advancements on the electrode and electrolyte components, batteries also gained more interest in the electric transportation and renewable energy storage fields. The potential of this technology offers further expansion of its area of use from robotics to space, making lithium batteries the power sources of the future.

Studies on technology and future projections show that batteries along with the electric system shall progress in means of power, energy capacity, and reliability. National Academy, reports on commercial aircraft propulsion and energy systems research that battery specific energy shall go beyond 1800 Wh/kg, in order to have regional and single-aisle civil aircraft to be all-electric. Comparing the technology targets to be around

- developing methods to re-use the batteries
- using incentive tools to achieve growth in the market.

Also, further developments in electric motor power density and power electronics are well-studied areas that will make electric propulsion possible in the future [51]. The mentioned areas of further research are also in other domains like automobile and naval applications, which will benefit both technology and dual-use advantages.

Energy storage technologies such as embedded in multifunctional structures, hybrid batteries, energy harvesting techniques are being studied besides progress on battery electrochemistry technologies in order to achieve technology limits for making commercial future electric aviation possible [52].

3. CONCLUSION

Aviation is in the search for greener technologies, while cost-effectivity and reliability is the primary concern. Electric aviation seems at a key role starting from the 1980s. Attempts for all-electric aircraft showed that there is still a way ahead in means of subsystem technology development. Also, it is seen that the aviation industry also needs a new "system-wise" approach to design. While general focus is given on power electronics, batteries are also an important part of the aircraft systems, for achieving greener targets.

In this survey study, the electrification of aviation is reviewed with technological advancements over time. It can be seen that more electric concept is developed while the ultimate goal of all-electric propulsion is studied.

It can be seen that, in the past, as the technologies progress, backward compatibility was the main concern due to the conservative nature and costs related to aviation specifications. Today, the electrification of aviation exhibits new opportunities for the overall renewal of the system approach without compromising safety, maintainability, and effectivity. Although in the 1980s subsystem level developments were seen as adequate, a new bottom-up approach for the whole system is needed as mentioned in the literature.

While the research focus is given to effectivity of generating, transporting, and control of electric energy, storage is also a major bottleneck. Recent battery research shows very high capacities in the lab tests, with the possibility to be industrialized in near future.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Melih YILDIZ: Performed the experiments and analyses the results. Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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