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Analysis of the performance of an aircraft powered by hybrid propulsion

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Travel is an inseparable part of human life. It is connected not only with private life but also with business life. People want to travel more, farther and faster. That is why air transport is currently one of the fastest-growing areas of passenger transport, and airlines carry more and more passengers from year to year. Due to the growing negative impact of air transport on the natural environment, research aimed at the development of technologies to reduce the negative impact of air transport is becoming more and more important. One of the possibilities for improving the situation is the use of alternative energy sources, limiting the emission of greenhouse gases into the atmosphere. The paper aimed to analyze the meaningfulness of replacing the classic power unit in a light transport aircraft with a hybrid, combustion-electric power unit. Analyzes were made with the use of simulation methods for the PZL M-28 aircraft.

Key words: *air transport, hybrid power unit, electric aircraft, Small Air Transport (SAT), aircraft emission*

1. Introduction

According to ICAO's annual global statistics, the total number of passengers carried by regular services in 2019 was 4.5 billion, and the number of flights reached 38.3 million [1]. 11.1 million flights were made in the ECAC area. Eurocontrol's forecast for 2027 predicts an increase in the number of flights in the ECAC area by 6 to 17% [2].

Unfortunately, the development of aviation is also associated with an increase in carbon dioxide emissions to the environment. Research shows that aviation is responsible for over 2% of global carbon dioxide emissions [3]. Carbon dioxide is not the only product of fuel combustion. Nitrogen and sulphur oxides as well as soot also have atmospheric altering properties. In 2017, air navigation was responsible for 3.4% of total green-house gas emissions [4]. Although it is not the highest source of greenhouse gas emissions, it is in this sector that the greatest increase in the production of atmospheric pollutants is noticeable. Forecasts suggest that aviation could be responsible for 20.2% of global green-house gas production in 2050 [5].

According to the Intergovernmental Panel on Climate Change (IPCC), global greenhouse gas emissions must fall by around 60% by 2050. Only thanks to this will it be possible to achieve the assumed climate goal [6]. The International Civil Aviation Organisation (ICAO) plans, after 2021, to initiate the Program of Compensation and Reduction of Carbon Dioxide Emissions in International Aviation (CORSIA) [7]. The purpose of this program is to help tackle the problem of the annual increase in CO_2 emissions from international civil aviation. Aircraft operators are tasked with monitoring and reporting the fuel consumption of international flights in order to determine their annual carbon dioxide emissions. Title offsetting is based on emissions trading, not emissions reduction – aircraft operators will have to buy carbon credits from the carbon market [8]. The International Air Transport Association (IATA) is also striving to reduce emissions of harmful gases. Its goal is to achieve net CO_2 emissions of 50% of 2005 emissions by 2050 [7].

The need to reduce the emissions of air transport was a factor that initiated work on the search for new types of power units and new fuels for transport aircraft. Aviation fuels must have certain properties, the most important of which are: excellent combustion properties, low viscosity, high energy density and low freezing point. Among the potential candidates for the fuel of the future aircraft, hydrogen seems to be the ideal solution because it has very good energy properties and is also environmentally friendly. In aviation, hydrogen can be used in two ways – as a replacement for petroleum fuels in large aircraft or in fuel cells to produce electricity. The second solution is intended for smaller transport aircraft. Unfortunately, replacing kerosene with hydrogen requires modification of both the aircraft and the entire aviation fuel production and distribution system. Hydrogen must be stored at low temperature and in well-insulated tanks, 3 times larger in volume than current kerosene fuel tanks [9, 10].

Electricity can also be a fuel substitute. Fully electric power units are popular in the automotive market, especially in cars and ships. Research typically divides electric drives into three main groups:

– fully electric drive,
– turboelectric drive,
– hybrid electric drive.

Unfortunately, only a small number of experimental aircraft use electric propulsion. This is mainly due to insufficiently developed battery technology, which limits the flight range [12]. Research conducted by Safran has shown that a small aircraft needs cells with a specific energy of at least 500 Wh/kg for flight, which is much more than lithium-ion batteries can offer. An alternative for them could be lithium-air batteries with the theoretical specific energy of 11500 Wh/kg [13], unfortunately their lifetime is insufficient when it comes to use in the aviation industry. Lithium-sulfur batteries seem to be the most promising replacement for lithium-ion batteries. It is predicted that by 2030 their specific energy may reach the value of 650 Wh/kg and their service life in the range of 1500–2500 cycles [11].

Nevertheless, in Norway it is planned that by 2040 all short-haul flights will be performed by electric aircraft [22].

The situation is a bit different in the case of a hybrid-electric aircraft, where the weight of the load carriers is smaller. On the basis of research by Geiß and VoitNitschmann, it was found that hybrid-electric general aviation aeroplanes, designed for short-range missions, are able to use less energy than conventional aircraft [14]. Airbus, in collaboration with Siemens and Rolls-Royce, proposed the creation of a hybrid airliner. Their design, called the E-Fan X, involved replacing one of the four jet engines with an electric motor [15]. Unfortunately, in 2020, a year before the first flight of the pioneering machine, the companies announced the end of the demonstration program.

The solution that can revolutionize the aviation industry is the use of fuel cell (FC) technology and a hybrid energy storage system (HESS). Fuel cells are a quiet and clean source, and additionally, the energy density of hydrogen tanks is definitely higher than in batteries [20]. Unfortunately, the power density of fuel cells is insufficient. Battery energy storages are characterized by high energy conversion efficiency (nearly 85%), high response speed and high power density (output current up to 5C) [21]. Combining fuel cells with a hybrid energy storage system can improve the mileage, dynamics and economy of vehicles. Considering the above advantages, such connections may have a promising future in aviation applications.

2. Methodology

The concept of hybrid propulsion in aviation is at a low level of technological maturity. Currently, research and development works are carried out on the development of the concept of using hybrid drives. They are supported by experimental tests carried out with the use of stationary laboratory test stands or with the use of light unmanned aircraft or motor gliders. Currently, it is not possible to conduct experimental research with the use of light, real-size transport aircraft. For this reason, the basic research method used in research on hybrid power units in aviation is the computer simulation method. It requires building, verification and validation of mathematical models, selection of appropriate tools and research methods as well as methods for analysing the obtained results.

Research problem: currently available technological solutions do not allow passenger flights with hybrid-powered planes. The main limitation is the selection of the electric motor, batteries needed to power it and a less powerful internal combustion engine so that the take-off weight (estimated) of the aircraft does not exceed its maximum take-off weight.

Hypothesis: the optimal distribution of power between the internal combustion engine and the electric motor, which together form a hybrid propulsion, can allow to fly a satisfactory distance.

Objectives: the main objective of the study is to select the components of a hybrid drive in such a way that it can replace the internal combustion drive powering the PZL M28 class aircraft, which consists of two PT6A-65B engines.

Research methods: the study used the computer simulation method. The MATLAB Simulink program was used to carry out the simulation.

General research plan:

1. Building and verification of needed mathematical models
2. Case study
3. Analysis of the obtained results
4. Analysis of the impact of new technologies on aircraft performance

3. Models definition

A hybrid drive is a combination of at least two types of drives for moving one device. A Hybrid Electric Drive (HEP) is a combination of two or more energy sources, at least one of which is electrical. Of the many types of hybrid electric drives available on the market, the most popular is the series and parallel connection of an electric motor with a combustion engine. Figure 1 shows a schematic of the hybrid drive that served as the starting point for creating the mathematical model.

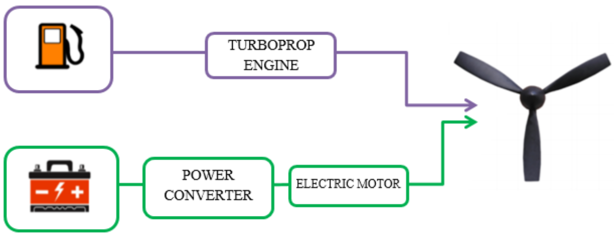

Fig. 1. Diagram of a hybrid drive

The analyzed mathematical model includes the following assumptions: the plane is not affected by any external forces, the plane is treated as a material point, and the flight takes place in the atmosphere with the parameters of a standard atmosphere.

It was assumed that the aerodynamic characteristics of an aircraft with a hybrid propulsion did not change compared to an aircraft with a traditional propulsion. The classical approximation of the aerodynamic characteristics in the aerodynamic polar, which is a square approximation of the drag coefficient as a function of the lift coefficient, was used. The minimum drag coefficient was estimated at 0.028 and the Oswald efficiency factor at 0.8.

The take-off weight of an airplane consists of the weight of the empty airplane, engines weight, fuel weight, weight of crew, batteries weight as well as the weight of passengers and their baggage. Therefore, the formula for the take-off weight of an airplane is as follows:

$$m_{to} = m_{empty} + m_{cr} + m_{pax} + m_{bag} + m_{en} + m_{fuel} + m_{bat} \quad (1)$$

The only constant value in this equation is the weight of the empty aircraft (m_{empty}), but it varies depending on the airframe model chosen. The weight of the crew (2) depends on the number of its members (n_{cr}):

$$m_{cr} = 85\ n_{cr} \quad (2)$$

Weight of passengers (3) and baggage (4) are closely related to number of passengers (n_{pax})

$$m_{pax} = 85\ n_{pax} \tag{3}$$

$$m_{bag} = 20\ n_{pax} \tag{4}$$

The weight of electric and turboprop motors depends on three variables. The first one is the power of the motors they have to replace (P). The second variable is power-to-weight ratio of the electric motor (PWR_e) and power-to-weight ratio for turboprop engine (PWR_t). The third variable is the power share between electric motors and turboprop engines. Depending on the selected variant, it will vary from 0% to 100%. So if electric motors will be responsible for x% of the total power needed, then turboprop engines will be responsible for (100–x)% of the power. Taking into account all variables, the weight of the engines (5) can be calculated from the following formula that takes into account the assumed power split between the electric and the turboprop engine:

$$m_{en} = \frac{x\%\cdot P}{PWR_e} + \frac{(100-x)\%\cdot P}{PWR_t} \tag{5}$$

The weight of fuel, as well as weight of engines, depends on the power share between the electric motors and turboprop engines, but also on the flight distance (s), flight speed (V) and the specific fuel consumption (SFC). The created model analyzes only a horizontal flight at a constant altitude with a constant speed. Additionally, it does not take into account the change in fuel weight during the flight to compensate for the first assumption, a 20% fuel reserve is made, and then to compensate for the second assumption, the weight of the fuel is averaged by dividing it in half. Taking into account all variables, the fuel weight can be calculated from the following formula which only considers the fuel consumed by the turboprop engine for the assumed power split:

$$m_{fuel} = \frac{1.2\cdot\left(\frac{s}{V}\cdot SFC\cdot*(100-x)\%\cdot P\right)}{2} \tag{6}$$

The weight of batteries largely depends on the selected battery type and its specific energy (E_{wb}), but it is also dependent on the efficiency of the electric motor (η_e), flight distance (s) and flight speed (V). As in the case of fuel weight, a reserve of 20% is taken to compensate for the lack of calculations for the take-off, climb and landing phases. Therefore, the weight of the battery can be calculated from the formula which takes into account the mass of the battery resulting from the power required of the electric motor for the assumed power split:

$$m_{bat} = 1.2\cdot\frac{\frac{x\%\cdot P}{\eta e}\frac{s}{V}}{E_{w_b}} \tag{7}$$

Using the formulas (2)–(7) and (1) the take-off weight of the airplane can be calculated. The necessary condition that must be met in order for the combustion engine to be replaced with a hybrid propulsion is such that the calculated take-off weight of the airplane cannot be higher than its maximum permissible take-off weight:

$$m_{to} \le MTOM \tag{8}$$

The formulas presented above were used to create a computer simulation model in the MATLAB Simulink. The diagram of the above-mentioned model is presented in Fig. 2.

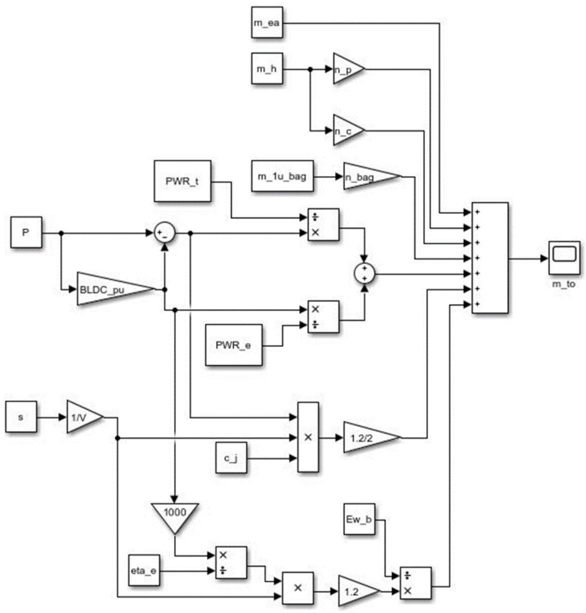

Fig. 2. Simulation model

4. Case study

Computer simulation in MATLAB Simulink has been performed for the PZL M28 class aircraft powered by two PT6A-65B turboprop engines from Pratt&Whitney Canada with a total power of P = 1640 kW. The crew of the selected aircraft consists of 3 people. Despite the fact that the maximum permissible number of passengers is 19, the research assumed that there would be 10 people on board. As part of the research carried out for the purposes of this article, three variants of the percentage power share into electric motors and turboprops are analyzed. Variant „A" assumes that 25% of the power will come from electric motors and 75% from turboprop engines. In variant „B" an equal division of 50% was assumed. Variant „C", on the other hand, assumes that 75% of the power will be generated by electric motors and 25% by turboprops. The weight of empty airplane is equal to m_{empty} = 3654 kg.

In order to be able to count the weight of electric motors and turboprop engines for consecutive variants, it is necessary to know the PWR_e and the PWR_t. There are various types of electric motors available on the market, but due to the reliability and high specific power values, the best choice is the high power density brushless motor. The power-to-weight ratio of the selected type of electric motor is [16]:

$$PWR_e = 2.68\ \frac{kW}{kg} \tag{9}$$

The power-to-weight ratio of the turboprop engine was calculated with the use of generally available data concerning the turboprop engines available on the market. It is:

$$PWR_t = 3.64\ \frac{kW}{kg} \tag{10}$$

For the calculation purposes, it was assumed that the speed of the aircraft will be V = 270 km/h, and the flight distance s = 80 km. The SFC was calculated on the basis of data from several different turboprop engines. It is:

$$\mathrm{SFC} = 0.328\,\frac{\mathrm{kg}}{\mathrm{kWh}} \tag{11}$$

A lithium-ion battery was selected to power the electric motor, the specific energy of which is [17]:

$$E_{w_b} = 250\,\frac{\mathrm{Wh}}{\mathrm{kg}} \tag{12}$$

The efficiency of the electric motor was assumed to be η_e = 0.95. The necessary condition that must be met in order for the combustion engine to be replaced with a hybrid propulsion is such that the calculated take-off weight of the aircraft cannot be greater than its maximum take-off weight. The maximum take-off weight of the PZL M28 is:

$$\mathrm{MTOM} = 7500\ \mathrm{kg} \tag{13}$$

Calculations were made using the simulation model created and the data collected above concerning the discussed case. The obtained results are presented in Table 1.

Table 1. Calculation results

Symbol		Value
m_{empty}		3654 kg
m_{cr}		255 kg
m_{pax}		859 kg
m_{bag}		200 kg
variant „A”	m_{en}	491 kg
variant „B”		531 kg
variant „C”		572 kg
variant „A”	m_{fuel}	71.7 kg
variant „B”		47.8 kg
variant „C”		23.9 kg
variant „A”	m_{bat}	613.8 kg
variant „B”		1227.6 kg
variant „C”		1841.4 kg
variant „A”	m_{to}	6135.5 kg
variant „B”		6765.7 kg
variant „C”		7395.9 kg

5. Results and discussion

5.1. Dependence of take-off weight on flight distance for different power splits

Figure 3 shows the dependence of the airplane take-off weight on the flight distance. The calculations were carried out assuming that there are 3 crew members and 10 passengers with baggage on board, and the cruising speed of the plane is 270 km/h.

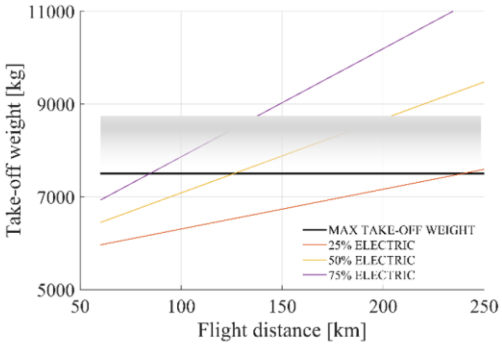

Fig. 3. Graph of dependence of take-off weight on flight distance for different power share

The chart shows that an airplane powered in 25% by electric motors and 75% by turboprop engines can fly the greatest distance. This distance is 239 km, which is about 16% of the maximum distance that the PZL-M28 can travel. The aircraft powered in 50% by electric engines and 50% by turboprop engines can fly only 126 km. Increasing the share of electric motors to 75% will reduce the flight distance to 84 km.

5.2. Dependence of take-off weight on flight distance for different number of passengers

Figures 4–6 show the dependence of the airplane take-off weight on the flight distance for a different number of passengers taken on board for three variants of the power splits into electric motors and turboprop engines. In each of the following cases, the plane is flying at a speed of 270 km/h and there are three crew members on board.

The number assigned to a specific line in the graphs represents the number of passengers taken on board. The maximum take-off weight of an airplane is a limit that cannot be exceeded with the specific number of passengers on board. This means that everything on the graphs above the black line representing the maximum take-off weight of the airplane does not meet the necessary condition and must be discarded.

A. power share – 25% electric motor 75% turboprop engine

Figure 4 shows the dependence of the airplane take-off weight on the flight distance for a different number of passengers for variant "A". It is clear that the longest flight can be with one passenger on board, although even in this case it will not be possible to travel a route longer than 375 km.

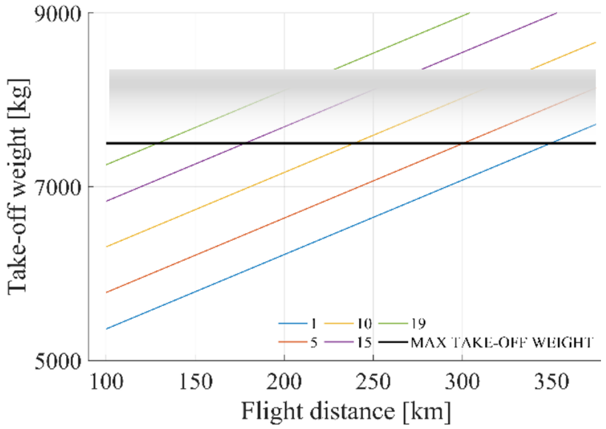

Fig. 4. Graph of the dependence of take-off weight on the flight distance for a different number of passengers– variant „A”

B. power share – 50% electric motor 50% turboprop engine

Figure 5 shows the dependence of the airplane take-off weight on the flight distance for a different number of passengers for variant „B”. Increasing the consumption of power from electric motors is associated with reducing the distance that the plane can fly. Taking 19 passengers on board, the plane can fly no longer than 67 km.

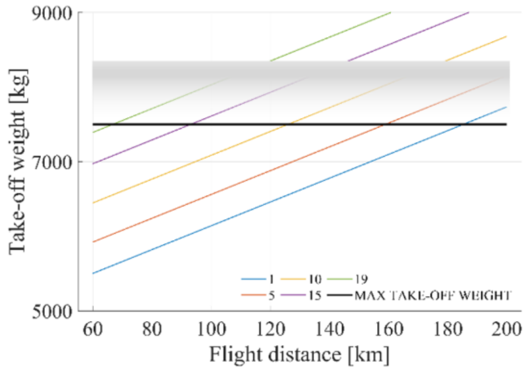

Fig. 5. Graph of the dependence of take-off weight on the flight distance for a different number of passengers– variant „B"

C. power share – 75% electric motor 25% turboprop engine

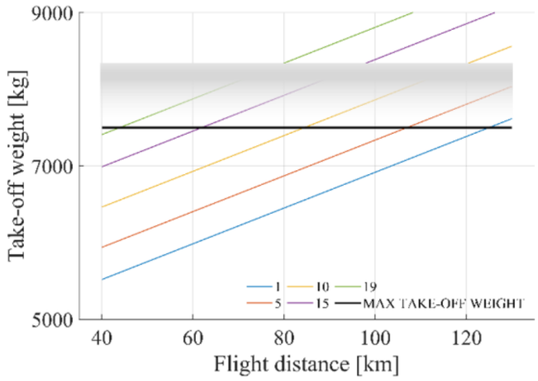

Fig. 6. Graph of the dependence of take-off weight on the flight distance for a different number of passengers– variant „C"

Figure 6 shows the dependence of the airplane take-off weight on the flight distance for a different number of passengers for variant „C". Where most of the power comes from electric motors, an airplane with one passenger can fly over 125 km. If there are 15 passengers on board, the distance drops to about 60 km.

6. The impact of new technologies

The main factor that inhibits the growth of interest in airplanes powered by fully electric or hybrid engines is the low specific energy of the battery and the insufficiently high power-to-weight ratio for the electric motor. This chapter focuses on the analysis of the dependence of the airplane take-off weight on the flight distance for three different percentage power splits, assuming that the lithium-ion battery was replaced with a lithium-air battery with specific energy:

$$E_{w_b} = 11{,}680\,\frac{\text{Wh}}{\text{kg}} \tag{14}$$

and that the power-to-weight ratio for the electric motor is:

$$\text{PWR}_e = 5\,\frac{\text{kW}}{\text{kg}} \tag{15}$$

Figure 7 consists of 3 graphs and shows the dependence of the airplane take-off weight on the flight distance at three different power splits. It was assumed that there are 3 crew members and 10 passengers with their baggage on board, and the cruising speed of the plane is 270 km/h. Calculations were made for the following four variants:

- Variant I
  - $\text{PWR}_e = 2.86\,\frac{\text{kW}}{\text{kg}}$
  - lithium-ion battery, $E_{w_b} = 250\,\frac{\text{Wh}}{\text{kg}}$
- Variant II
  - $\text{PWR}_e = 5\,\frac{\text{kW}}{\text{kg}}$
  - lithium-ion battery, $E_{w_b} = 250\,\frac{\text{Wh}}{\text{kg}}$
- Variant III
  - $\text{PWR}_e = 2.86\,\frac{\text{kW}}{\text{kg}}$
  - lithium-air battery, $E_{w_b} = 11{,}680\,\frac{\text{Wh}}{\text{kg}}$
- Variant IV
  - $\text{PWR}_e = 5\,\frac{\text{kW}}{\text{kg}}$
  - lithium-air battery, $E_{w_b} = 11{,}680\,\frac{\text{Wh}}{\text{kg}}$

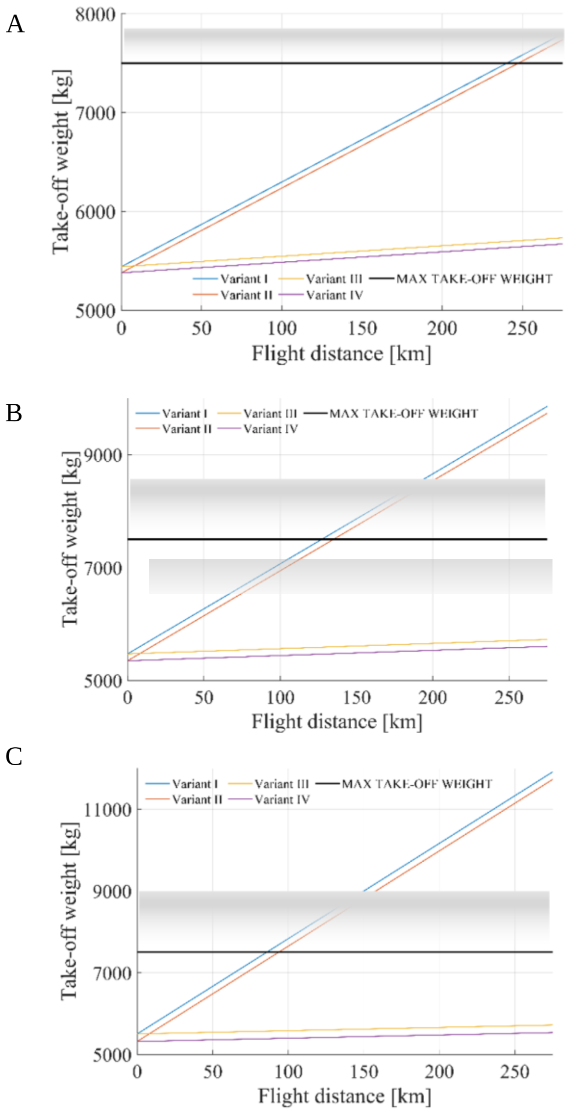

Fig. 7. Graph of the dependence of the take-off weight on the flight distance for the power split of: A – 25% from electric motors and 75% from turboprop engines, B – 50% from electric motors and 50% from turboprop engines, C – 75% from electric motors and 25% from turboprop engines

The graphs show that changing the electric motor, whose power-to-weight ratio is 2.86 kW/kg, to one whose ratio is 5 kW/kg, will slightly extend the distance that the plane can fly. The comparison of these distances is shown in Fig. 8. The biggest difference in distance that can be travelled when a lithium-ion battery is changed to an air-lithium battery. In these two cases, for the first time, increasing the share of power from electric motors increases the distance that the plane can fly. It is enough for electric motors to be responsible for 50% of the required power so that the maximum distance that the PZL-M28 would be able to fly exceeds the maximum distance of this aircraft according to the Flight Manual.

Table 2. Maximum distance for maximum take-off weight for different variants and different power share

25% electric, 75% turboprop	
variant	Distance [km]
I	169
II	176
III	1358
IV	1434
50% electric, 50% turboprop	
variant	Distance [km]
I	88
II	97
III	1522
IV	1676
75% electric, 25% turboprop	
variant	Distance [km]
I	59
II	69
III	1730
IV	1999

Summary

The calculations which was made as part of this study were to prove that it is possible to replace the internal combustion engine of a small passenger aircraft with a hybrid electric drive.

The conducted analyzes are intended to demonstrate the reasonableness of the development of hybrid power units in small transport aviation. Technological progress in the field of batteries will make the analyzed solutions even more attractive from the point of view of reducing transport aircraft emissions. They may also justify undertaking further research and experimental work, which will be characterized by higher costs and workload.

The presented results complement the research conducted so far, which mainly focuses on fully electric aircraft. The analyzed solution seems to be more attractive, due to the level of technological development of electric drives, concerning commuter-class transport aircraft.

The performed calculations, taking into account the adopted assumptions, showed that such a replacement is possible. However, it should be remembered that the change of the type of propulsion may, to some extent, limit the throughput of the aircraft or the number of passengers taken on board will have to be reduced, for example, the aircraft powered in 25% by turboprop engines and in 75% by electric motors with 10 passengers on board is able to overcome only 84 km, while when there are only 3 passengers on board, this distance increases by 36.9% to 115 km. In the case of an aircraft powered by in 50% by turboprop engines and in 50% by electric motors, the same change in the number of passengers will increase the travel distance by 36.5% from 126 km to 172 km. In the case of an aircraft powered in 75% by turboprop engines and in 25% by electric motors, the increase will be 35.9% with an increase in distance from 239 km to 325 km. This means that regardless of the percentage power share into electric motors and turboprops, a change in the number of passengers has the same effect on extending or shortening the travel distance.

An aircraft powered to a greater degree of turboprop engines can travel more than twice as far as its counterpart powered by more green energy. This is due to the lack of a battery with the appropriate specific energy.

Nevertheless, the research carried out for the air-lithium battery clearly shows that with the development of the battery, hybrid drives can be used more and more in the aviation industry. The calculations show that when the lithium-ion battery is replaced with a lithium-air battery, the aircraft powered as described above with 10 passengers on board will be able to cover 1730 km, which is more than the PZL M28 powered only by internal combustion engines can overcome.

Nomenclature

Ewb specific energy [Wh/kg]
m_{to} takeoff weight [kg]
m_{empty} aircraft empty weight [kg]
m_{cru} crew weight [kg]
m_{pax} passengers weight [kg]
m_{bag} baggage weight [kg]
m_{en} engines weight [kg]
m_{fuel} fuel weight [kg]
m_{bat} battery weight [kg]
MTOM maximum teakoff mass [kg]
n_{cru} number of crew
n_{pax} number of passengers
P power of the engine [kW]
PWR_e power-to-weight ratio of the electric motor [kW/kg]
PWR_t power-to-weight ratio for turboprop engine [kW/kg]
V speed of flight [km/h]
η_e efficiency of the electric motor

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