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Development and research of a hybrid power unit for ultralight aircraft: an innovative approach to energy efficiency and operational flexibility

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This scientific article presents an innovative concept of a hybrid power unit designed for ultralight aircraft, with the aim of improving energy efficiency and operational flexibility. As part of the development of the system, the construction of the combustion unit and the electric motor / generator, which are the key elements of this solution, was described. The advanced internal combustion engine controller and the bi-directional energy conversion converter have been developed and built to enable optimal cooperation of both energy sources. In order to carry out experimental research on the developed system, a special test stand was built on which a prototype drive unit was mounted. The results of the research include preliminary performance characteristics of the prototype drive unit and an analysis of the achievements that indicate the potential benefits of using such a hybrid drive unit. The article also summarizes the conclusions and recommendations for further work on improving this innovative solution.

Key words: *hybrid drive, electric motor, combustion engine, transmission, energy optimization*

1. Introduction – development of the concept of hybrid and electric aircraft propulsion

Over the past decade, innovative ideas for fully or partly electrically powered aircraft have sparked discussions in the general community as well as intense media coverage. As a result, a significant number of start-up companies have been created that seek to commercialize electric and hybrid propulsion technologies for aircraft (Electric Propulsion, EP). Rapid developments in this area can also be observed in the technical literature. In the years 2006–2009, there was an average of one article per year on the design and analysis of electric and hybrid aircraft, while from 2015 the number of these articles increased to nearly twenty per year [9].

The main factor driving public interest in the electrification of aviation is the desire to reduce the negative impact on the environment. NASA's Subsonic Fixed Wing program has set ambitious targets for energy consumption, nitrogen oxide (NO_x) emissions and noise for three generations of aircraft to enter service by the 2030s [4]. In 2013, after a series of studies on conceptual design conducted by industry and academia, these goals were updated [9]. The most aggressive performance targets are for the "N+3" generation, which is expected to be operational in the mid-2030s. These include noise reduction at the level of –55 dB at the airport border, reduction of NO_x emissions by 75% and reduction of fuel consumption by 70% compared to the technology from 2006 [9].

The International Civil Aviation Organization (ICAO) has established noise and NO_x certification standards in 2020 [13] and a voluntary carbon offset program to keep carbon emissions at 2020 levels [2]. NASA-funded research results (discussed in Chapter 3) show that electrification can improve carbon, noise and NO_x performance, enabling the civil aviation fleet to meet its N+3 targets [2].

Electric vertical take-off and landing (e-VTOL) operational concepts have been promulgated by a number of start-ups and mature enterprises around the globe, such as Volo-Copter, Ehang, Zee Aero, Joby Aviation and Airbus. The tech giant and transportation company Uber, in its white paper "Elevate" published in 2016, argued that there is a significant market for point-to-point urban air mobility that could drive action in this new segment [18, 20, 21]. Due to noise and cost, proponents of e-VTOL argue that traditional helicopters are not the right architecture for this type of application. This review focuses on fixed-wing aircraft, leaving the booming e-VTOL segment to other market analysts.

The extensive literature in the field of EP fixed wing aircraft offers numerous review articles that provide a partial overview of the area. A particularly extensive and understandable, though not technical, summary of aviation electrification from a business perspective is presented in papers [10, 18] presenting an overview of EP architectures and some basic sensitivity analyzes based on the Breguet equation. In turn, in [1], he focuses on the practical aspects of conceptual design of hybrid passenger aircraft using low-order and graphical dimensioning methods. However, there is no discussion of higher-fidelity optimization tools or a comprehensive overview of design studies and demonstration programs.

Several other reviews include aircraft EP as a side topic in the context of another main issue [8] and [15] mainly distributed propulsion with extended coverage of EP. Papers [7, 17] present an excellent overview of more electric aircraft systems, which includes the aspect of aircraft propulsion and design solutions.

One of the most promising trends in the construction of hybrid and electric engines for ultralight aircraft is the development and implementation of battery technology with higher energy density. Improving the energy density of batteries will significantly increase the range and flight time of ultralight electric aircraft. Higher energy-density batteries also have the potential to increase the overall efficiency of hybrid engines by allowing for greater use of electricity versus fossil fuel.

Another major trend is the development of more efficient energy management systems for hybrid and electric motors. These systems, which control how and when energy is delivered to the engine, can significantly improve the aircraft's energy efficiency. They are particularly relevant for hybrid aircraft that have to balance the use of electricity and fossil fuel. Finally, companies and research institutes around the world are working on new technologies and materials that can make electric motors more efficient. For example, innovations in the field of superconducting materials could lead to electric motors with higher efficiency and lower weight.

It seems that the future of ultralight hybrid and electric aircraft is certain. With the continuous development of battery technology, energy management systems and electric motors, we can expect these aircraft to become more efficient, sustainable and accessible to a wider range of users. This represents great opportunities for the aviation sector as well as environmental benefits.

Recent years have been full of dynamic discussions of scientists and engineers from universities and the aviation sector on research into aircraft powered entirely or partially by electricity. The constantly growing need to create more and more efficient and environmentally friendly aircraft leads to broadening technological horizons and attempts to implement previously unattainable concepts. Combustion engines play a dominant role in aircraft propulsion. They use fossil fuels with a high energy density, which is an undeniable advantage for the aviation industry. Unfortunately, they are also a significant source of pollution – burning fossil fuels leads to the emission of carbon dioxide, the main gas responsible for the global warming process [9].

According to data from the Air Transport Action Group (ATAG), 2% of carbon dioxide emissions generated by human activities come from aviation, and this number seems to be increasing year by year with the increasing number of aircraft [19]. In response to this trend, the International Civil Aviation Organization (ICAO) formulates strategies, updates emission standards and recommended practices, while conducting extensive outreach activities [11].

In addition to the issue of pollutant emissions, an important aspect is the limited availability of fossil fuels in the world. Aviation is estimated to account for around 2% of the world's total fuel consumption. It is not known how much more of these resources will remain available in the future, and the price of fossil fuels is definitely going up due to the growing global demand for energy.

In connection with all this, the search for alternative forms of propulsion becomes essential. Hybrid drives seem to be the perfect solution here. Batteries can be used as a source of energy instead of traditional fuels. Nevertheless, their use brings with it a number of challenges, such as the issue of weight on board an aircraft or the problem of recycling used batteries. However, the increasing intensity of research into battery technology gives hope for more frequent use of this energy source in aviation. It is worth remembering about a significant challenge related to international aviation regulations, which require a minimum level of safety to be guaranteed in the context of the use of batteries [5].

Compared to electric motors, internal combustion engines have a lower efficiency and power-to-weight ratio. That is why it is proposed to use hybrid systems that would be able to balance the benefits of both types of engines, thus improving performance. Hybrid propulsion systems have a number of potential advantages, such as lower fuel costs, less vibration, reduction of pollution and noise reduction, for example. Developing an all-electric powertrain that balances all these factors is a challenging task. This is necessary because it is critical to improving the physical limits of these propulsion solutions.

2. The potential of hybrid engines designed to propel ultralight aircraft

2.1. Development of hybrid engines in the world

In the cited study, a theoretical analysis of various design solutions for hybrid propulsion systems used in aircraft was carried out. This study focused on several design examples that are used in various aircraft designs. One of these examples is the Alatus single-seat ultralight aircraft, which has been equipped with a parallel hybrid propulsion system. This aircraft was developed at the University of Cambridge in 2010. The Alatus hybrid demonstrator consists of a 2.8 kW four-stroke internal combustion engine that is mechanically coupled to a 12 kW brushless electric motor. The electric motor is powered by lithium-polymer (Li-Po) batteries with a capacity of 2.3 kWh [8].

Another interesting example is the Garmex Soul airframe, which is also equipped with a parallel hybrid drive. This aircraft is manufactured by Garmex in the Czech Republic and was originally powered by a 200cc Bailey V engine with up to 15 kW power. However, to hybridize the powertrain, the Bailey motor was replaced with a 7.5 kW@7000 rpm Honda GX160 motor coupled to a 12 kW JM1 brushless DC motor that can also act as a generator to recharge the battery. Unlike Alatus, Garmex Soul has the ability to recharge the batteries during the flight and uses an electric motor to increase or maintain the torque on the drive shaft during altitude increase or take-off [6].

Simulation tests and checking the results of hybridization of the Garmex Soul airframe showed that the hybridization of the drive system can lead to fuel savings of up to 50% with a 60% hybridization degree. The greater the degree of hybridization, the greater the fuel savings, however, due to the limited energy density in the batteries, greater efficiency may be associated with a reduction in the range of the aircraft [3].

In addition, the works of T. Donateo on the hybridization of the Pro Mecc Freccia ultralight aircraft equipped with the Rotax 912 ULS engine (nominal power 73.5 kW at 5800 rpm) and a 3-blade propeller with a fixed pitch and a diameter of 1.75 m are aimed at improved safety. As part of this work, a hybrid drive system with a series-parallel architecture was proposed, which is based on automotive components. It consists of two electric motors, a scaled down Wankel motor and nickel metal hydride batteries [14, 15].

The purpose of the mentioned studies was to design the aircraft in such a way as to improve the safety of its use. The propulsion system based on automotive components enabled the use of an energy management strategy whose task is to control the state of charge of the battery and the operating point of the engine in order to minimize fuel consumption. The original configuration, consisting of a piston engine combined with a fixed-pitch propeller, was compared with a new hybrid propulsion system. Despite the higher take-off weight and lower maximum efficiency of the Wankel engine, the new configuration allowed to reduce fuel consumption by about 20%. The series-parallel hybrid architecture, together with the developed energy management strategy, behaves like a parallel hybrid during take-off and climb, thus ensuring high performance. During a normal operational voyage, the system operates as a continuously variable transmission system, with the battery being discharged and recharged cyclically. IN In the event of an engine failure, the hybrid system operates as an all-electric system and can bring the aircraft to a safe landing.

Hybrid aircraft, which use both combustion engines and electric propulsion, are currently an area of intense research and development in the field of aviation. The power source for the electrical systems in these aircraft are batteries, which play a key role in ensuring reliable and efficient operation of the system. This article focuses on the issues related to the use of electric batteries in hybrid aircraft, analyzing both the challenges and prospects associated with this technology.

One of the main challenges with electric batteries is their energy density, which is the amount of energy that can be stored per unit of weight. For aircraft where mass is critical to performance and range, it is essential to achieve the highest possible energy density to provide enough energy with the lowest possible battery mass.

Hybrid aircraft often require multiple battery charging and discharging cycles in a single flight. This puts additional demands on battery life and performance as they must be able to efficiently handle these cycles without significant performance degradation.

Electric batteries, especially high-capacity batteries, must meet stringent safety requirements to avoid the risks of overheating, short circuits and leakage. In the case of aircraft, safety is an absolute priority, so the design and management of batteries must take into account high safety standards, including monitoring, cooling and security systems.

Currently available battery technologies such as lithium-ion (Li-Ion) and lithium-polymer (Li-Po) form the basis for most hybrid aircraft. However, intensive research into new battery materials and designs is aimed at improving energy density, durability and safety, opening the way to more advanced battery technologies such as solid-state batteries and high-capacity batteries.

Effective energy management in hybrid aircraft, including optimal battery charging and discharging, is a key element in achieving high efficiency and range extension. The development of advanced energy management algorithms and integration with control and monitoring systems enable optimal use of available energy.

The development of hybrid aircraft is also associated with the need to develop an appropriate battery charging infrastructure. The development of effective and efficient charging stations, both at airports and elsewhere, is essential to ensure fast and reliable charging of aircraft batteries.

2.2. Development of hybrid aircraft engines in Poland

In Poland, as well as around the world, the motivation to conduct research on the hybrid propulsion system of ultralight aircraft is the need to increase energy efficiency and reduce emissions of harmful substances into the atmosphere. Ultralight aircraft, such as paragliders and gliders, are gaining in popularity due to their low cost and simplicity of construction. In the context of air transport, hybrid propulsion systems can be an effective alternative to internal combustion engines, enabling the increase of energy efficiency and reduction of operating costs of ultralight aircraft.

On the Polish aviation market, which is one of the fastest growing in Europe, the introduction of hybrid propulsion systems could significantly contribute to the development of the sector by increasing its attractiveness for users. Research on the hybrid propulsion system of ultralight aircraft is an important step towards the sustainable development of air transport and the improvement of air quality, not only on a Polish but also global scale. Their results may be used in the future to develop new, more ecological and effective propulsion solutions for ultralight aircraft.

One of the important aspects of this research is the presentation of the concept of operation and loads occurring in hybrid propulsion systems used in aviation. This will allow for a better understanding of the mechanisms of operation of these systems and assessment of their strength and reliability. In the context of Poland, such research can contribute to increasing the safety and efficiency of aviation in the country, for the benefit of passengers, air operators and the environment. In addition, an important aspect of research on hybrid drive systems is the analysis of structural relationships between the drive train assembly and the assembly of the main mechanism of the internal combustion engine. This is to better understand the impact of these components on the performance of the entire powertrain. Studying the ratio of electric and combustion drive is an important issue that often poses a challenge in the design of a hybrid drive. In the context of the Polish market, due to its dynamic development and innovation, such research can contribute to the development of new technologies and solutions that can be used in various sectors of the economy, not only in aviation.

According to many experts, the development of hybrid technologies is of key importance for the future of aviation in Poland and in the world. The aviation industry, both domestic and global, faces many challenges, including reducing CO_2 emissions, increasing energy efficiency and reducing noise. Research on hybrid propulsion systems, such as those carried out in Poland, can contribute to solving these problems and enable further development of aviation in a sustainable and ecologically responsible manner.

The conducted research works are ultimately aimed at presenting the proprietary hybrid engine design – a pioneering achievement that is a combination of many years of science, technological innovation and ecological awareness. This ambitious task includes the development of a prototype that, in addition to having the advantages of electric and internal combustion engines, will also be characterized by high durability, reliability and optimal performance parameters.

In the context of the specificity of hybrid structures, the goal is to ensure a balance between energy efficiency and power, taking into account aspects such as weight, cost and environmental impact. The main performance parameters that are taken into account are range, speed, energy consumption, as well as ease of use and maintenance.

Longevity is a key factor in aviation, and the design of a hybrid engine must take this aspect into account. Therefore, durability and reliability are integral elements of the design process. For example, engine components such as batteries and drive trains must be designed to withstand harsh operating conditions such as temperature changes, heavy loads and operating in a variety of weather conditions.

All these aspects, from environmental benefits to practical efficiency and durability, must be integrated into the final hybrid engine design to be presented as a result of this research. The goal is for this engine to be not only an innovative technological solution, but also a viable, practical alternative to traditional internal combustion engines, contributing to the sustainable development of aviation.

Hybrid aviation engines have many advantages that may contribute to their growing popularity in the aviation industry. Here are a few of them:

1. Reducing CO_2 emissions: Hybrid aircraft engines emit less carbon dioxide (CO_2) compared to traditional internal combustion engines. This emission reduction is key to reducing aviation's impact on climate change.
2. Energy Efficiency: Hybrid engines are typically more energy efficient than internal combustion engines. Thanks to the use of batteries and electric motors, they can use the energy recovered during processes such as braking.
3. Noise reduction: Hybrid engines are typically quieter compared to internal combustion engines. This aspect is particularly important in the context of urban aviation and the increasing pressure to reduce aircraft noise.
4. Fuel economy: Due to their higher energy efficiency, hybrid engines can provide fuel economy compared to traditional internal combustion engines.
5. Greater Reliability: Hybrid propulsion systems can improve aircraft reliability because the failure of one system (electric or combustion) does not result in a complete loss of power.
6. Lower cost of ownership: While the initial cost of investing in hybrid technology may be higher, long-term operating costs can be lower due to fuel savings and the ability to charge the battery with renewable energy.
7. Flexibility: Hybrid engines offer greater flexibility, allowing you to choose between electric or combustion propulsion depending on flight conditions and operational requirements. For example, an aircraft may use electric propulsion during take-off and landing to minimize noise and emissions, then switch to internal combustion when flying at higher altitudes.
8. Renewable energy support: Hybrid engines can support aviation's transition to renewable energy because the batteries can be charged with energy from renewable sources such as wind or solar power.
9. Smaller air pollution: In addition to reducing CO_2 emissions, hybrid aircraft engines can also reduce emissions of other harmful substances, such as nitrogen oxides and particulate matter, which are often emitted by traditional internal combustion engines.
10. Innovation: Hybrid technology is part of the future of aviation. Investing in this technology means investing in innovation, which can bring benefits in the form of new business opportunities and competitive advantage.
11. Potential Economic Benefits: Greater fuel efficiency, lower running costs and potential savings from emission regulations can bring economic benefits to airlines and other aviation operators that invest in hybrid technology.

3. Designing a prototype hybrid aircraft engine

3.1. Concept and theoretical assumptions

A deep analysis of design solutions used in hybrid propulsion systems of ultralight aircraft is a key aspect of the design and development process of these advanced systems. A thorough understanding of the design, mechanisms and functionality of these innovative propulsion systems is essential to determine the most effective and efficient technological solutions, which enables the development of precise design strategies.

Design analysis of hybrid powertrains allows the assessment of the impact of various design parameters on the overall efficiency and effectiveness of these systems. This gives engineers the ability to construct propulsion systems that are most suitable for specific operating conditions and optimize resource utilization. This understanding is fundamental to making strategic design decisions that can affect the efficiency, reliability and durability of these systems.

Engineers must consider a number of important factors when designing their own hybrid engine designs for ultralight aircraft, including but not limited to:

– The method of integrating the motors with the shaft of the drive system.
– Type of internal combustion engine and electric motor used in the hybrid drive system. Different types of engines can have significant differences in power, size, weight, efficiency and other key parameters.
– A type of transmission that connects an internal combustion engine and an electric motor. Different types of gears may have different characteristics such as gear ratio, weight, strength, etc.
– The power source of the hybrid propulsion system, i.e. aviation fuel or electricity from batteries. Each of these solutions has its own unique advantages and limitations.
– Type and construction of batteries used to power the electric motor.

- Power and efficiency of combustion and electric engines and their impact on aircraft performance and fuel consumption.
- Design and dimensions of engines and gears and their impact on the weight of the entire drive system.
- The level of noise and exhaust emissions generated by the hybrid drive system and the possibility of using a hybrid drive system in changing weather conditions.
- Costs related to the purchase, operation and maintenance of the hybrid drive system and their impact on the economic viability of this solution.
- Reliability and durability of the drive system and its ease of use and maintenance.

The series hybrid architecture of the powertrain is where only the electric motor is mechanically connected to drive devices such as fans. In this system, the internal combustion engine drives an electric generator, which in turn supplies power to the electric motor or charges the batteries using an advanced power management and distribution system. During phases of flight where relatively little propulsion effort is required (e.g. cruise phase), the energy converted by the generator can be used to charge the batteries, which increases the overall efficiency of the system.

Although the presence of additional electrical components in the powertrain architecture slightly reduces transmission efficiency, the overall improvement in powertrain efficiency is due to the ability to optimize the efficiency of the internal combustion engine and electric motor independently. Although the weight of the propulsion system may increase due to the additional electrical components, the potential increase in overall flight efficiency may offset these negative effects. As a result, properly balancing these various factors can lead to significant improvements in overall energy efficiency.

A key advantage of the series hybrid architecture is that the internal combustion engine is not mechanically coupled to the fan or propeller. This means it can run continuously at its optimum operating point, increasing its reliability and reducing maintenance requirements. The simplicity of the concept also leads to easy control of the propulsion, which enables a purely electric mode and the ability to recharge the battery in flight. However, there are some limitations, such as the fact that the electric motor must be able to deliver all the driving power, which can lead to weight gain. In addition, the efficiency of the system may be reduced due to the need for energy conversion. The series configuration is particularly suitable for designs requiring high torque and low speed, but may be less efficient compared to the parallel configuration. It is also important to take into account that it requires larger batteries and electrical devices, which leads to an increase in weight and volume of the entire drive system.

The complexity of these various factors underscores the complexity of the problem and shows how many different aspects must be considered when designing and analyzing hybrid propulsion systems for ultralight aircraft. These complex systems require a thorough understanding of the principles of engineering, life sciences, technology and economics. Achieving the optimal balance between these various factors is key to designing efficient, reliable and economically viable hybrid powertrains.

A thorough analysis of the design solutions used in hybrid drive systems is crucial not only to evaluate existing systems, but also to identify areas that can be improved, and even to create new innovative solutions. This process of analysis and innovation is essential for the continued development of hybrid powertrain technologies that have the potential to deliver significant benefits to the aerospace industry, including improved efficiency, reduced emissions, and overall improved energy efficiency.

Modern hybrid engines used in aircraft combine the energy efficiency of internal combustion engines with the flexibility and efficiency of electric motors. The use of such a configuration translates into a number of advantages, among which the increase in flight safety is particularly important. From the point of view of safety, the main advantage of hybrid systems is drive redundancy. In the event of failure of one of the engines (combustion or electric), the other can take over the driving role, ensuring continued control of the aircraft. This is especially important in emergency situations, when quick reaction and adaptation to new conditions can ensure a safe landing.

In addition, the electric motors, which are an integral part of the hybrid system, have excellent torque available from the start, which translates into quick start-up and response to changing flight conditions. Compared to internal combustion engines, electric motors are inherently more reliable and require less maintenance. Their design simplicity, no moving parts and no need for lubrication or cooling translates into a lower risk of failure.

In an energy context, however, the use of decoupling systems or additional gears may be more advantageous. This is for several reasons.

Decoupling the engine from the crankshaft allows the combustion engine and the electric motor to run independently of each other. The internal combustion engine can therefore be set to its most efficient operating point, which in turn reduces fuel consumption and emissions.

Additional gearing, while adding additional weight and complexity to the system, can help improve the overall efficiency of the drivetrain. They allow for a more precise adjustment of the rotational speed of the engines to the requirements of the different phases of flight, which in turn can lead to better energy efficiency.

The choice between these two configurations depends on the specific application and requirements. However, it is important to remember that safety and energy efficiency are not the only factors determining the final choice of drive configuration. Other important factors include the cost, weight and dimensions of the propulsion system, ease of operation and maintenance, and a number of other aircraft-specific parameters and limitations.

While electrically bonded hybrid systems provide greater reliability and redundancy, they can introduce additional complexities to the propulsion system, such as the need to manage power between the two propulsion sources, and the need to install and maintain additional components such as controllers and battery management systems. They can also introduce additional thermal and mechanical stresses on the internal combustion engine, which can affect its durability and performance.

Crankshaft decoupling systems or additional gearing, while they can provide better energy efficiency, can also introduce additional design and technological complexity. They may require additional mechanical components, such as clutches or gears, which can affect the weight, size and complexity of the drivetrain. In addition, they can also introduce additional mechanical stresses to the motors and other drivetrain components, which can affect their durability and performance.

Whichever drive configuration you choose, it's important to thoroughly understand all aspects of drive operation, such as motor performance, energy management, durability and reliability, and the costs and benefits of their use. Only then will you be able to make the right choice that best suits the specific requirements and constraints of your application. Therefore, further research and development of hybrid technology is crucial to further improve their efficiency, durability and safety, as well as to expand the range of their potential applications.

3.2. Internal combustion engines used for the hybrid system

The research engine, which is the subject of our description, is intended for use in hybrid systems. Optimizing its weight is crucial for use in ULM aircraft that do not exceed 120 kg. The research facility is a compact internal combustion engine whose weight does not exceed 35 kg, and yet it is capable of generating a maximum power of up to 42 kW.

As part of our research, this engine will be tested in two variants of the cooling system – liquid and air. Comparing the results from both of these versions will allow for an accurate assessment of the impact of the cooling method on engine performance and durability. The power technology of the internal combustion engine is based on multi-point fuel injection over the intake valve (MPI). This advanced fuel injection system, electronically controlled by a dedicated ECU, provides precise fuel dosing, resulting in increased engine efficiency and lower fuel consumption. Moreover, we plan to use innovative solutions to further increase the mechanical efficiency of the entire drive. One of them is the use of ceramic coating technology on selected components of the internal combustion engine. Ceramic coatings, due to their unique tribological properties, can significantly reduce friction in the motor, which translates into higher efficiency and longer life. Plus, we're going to use innovative technologies of casting molds made in 3D printing technology. This technology, although not yet widely used in the production of engines in the world, allows for the quick and effective creation of complex molds that can significantly improve the quality and efficiency of the production process. The importance of these innovative solutions in the tested engine is invaluable – they are intended not only to increase the efficiency and durability of the engine, but also to reduce its environmental impact by reducing exhaust emissions.

Engine model: 40i

The 40i engine parameters are presented in Table 1. The displacement of 627 cm^3, which has a major impact on its efficiency. The compression ratio is 8.5, which allows for efficient fuel combustion. The maximum power of the engine is 25.74 kW, generated at a rotational speed of 4640 rpm. At lower revs, 3630 rpm, the engine generates a continuous power of 22.06 kW. Torque is 58.3 Nm, generated at 3630 rpm, which guarantees strong acceleration and good performance at low and medium revs.

Table 1. 40i engine parameters

Parameter	Unit	Value
Displacement	cm^3	627
Bore	mm	75,5
Stroke	mm	70,0
Compression ratio	–	8,5
Maximum power at rotation speed	kW	25.74 at 4640 rpm
Continuous power at rotation speed	kW	22.06 at 3630 rpm
Torque at rotation speed	Nm	58.3 at 3630 rpm
Weight	kg	33.2

The engine weighs 33.2 kg (without fluids, fuel pump, fan and shrouds, with oil filter, starter motor and alternator fitted), which allows it to be used in light aircraft units. The propeller is driven by an indirect toothed gear, and the direction of rotation of the propeller is left-hand rotation. The fuel system is based on multi-point fuel injection with electronic control, and the ignition system is also electronically controlled. Engine control is carried out by the ECU EMU Classic model.

The engine has a working range from 950 (±50) rpm in idle (warm engine), to a maximum of 4700 rpm. The operating speed of the engine is 2200–4000 rpm, and the reducer ratio is 1.77. Propeller rotation at maximum engine speed is 2655 rpm. Among the pressures, it is worth noting the minimum operating oil pressure – 28 PSI = 1.9 bar (at 2000 rpm and 70°C oil temperature), and the maximum operating oil pressure is 65.3 PSI = 4.5 bar. Average operating oil pressure is 43.5 PSI = 3.0 bar.

The fuel recommended for use with this engine is car petrol with LO 98, and the oil – for ambient temperatures from 0 to +35°C – 5W-50 synthetic oil.

The Model 40i engine is designed for a variety of operating pressures and temperatures. The maximum oil pressure can be as high as 90 PSI or 6.2 bar, but only when the engine is cold. The fuel pressure should be between 2.8 and 3.2 bar. Nominal compression pressure ranges from 114 to 142 PSI, which translates to 8.9–10.8 bar.

In the temperature range, the minimum temperature for CLT start is 71°C. The maximum oil temperature is 135°C, and the through-flow oil temperature should oscillate between 110–120°C. The temperature of the CLT cruising head ranges from 100 to 137°C. The EGT exhaust gas temperature ranges from 680 to 750°C and the maximum EGT exhaust gas temperature is 850°C. In addition, the model 40i engine has limits in the form of a mass moment of inertia of the propeller, which should not exceed 930 $kg \cdot cm^2$. These detailed technical and operational parameters make the 40i engine a high-performance unit capable of operating in a wide range of operating conditions.

In the process of designing and testing the hybrid system, three engine concepts were originally considered. Each of them differed in cylinder configuration, which affected various aspects such as performance, balance and size.

The first concept is an in-line four-cylinder engine (Fig. 1). This arrangement, in which all cylinders are placed in one line, is well known for its simplicity and efficiency. It is also relatively easy to manufacture and maintain, which makes it attractive from a cost perspective. The measurement capabilities of this stand are shown in Fig. 2.

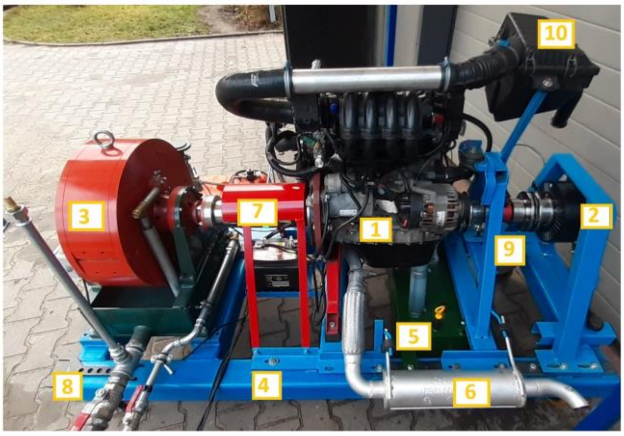

Fig. 1. View of the stand in a hybrid combination with a 4-cylinder in-line engine: 1 – 4-cylinder IC engine, 2 – EMRAX electric motor, 3 – water-cooled Eddy current brake, 4 – test stand main frame, 5 – engine oil tank, 6 – exhaust system, 7 – drive shaft between ICE and brake, 8 – cooling system connections, 9 – drive shaft between ICE and EMRAX with torque sensor, 10 – ICE intake air filter

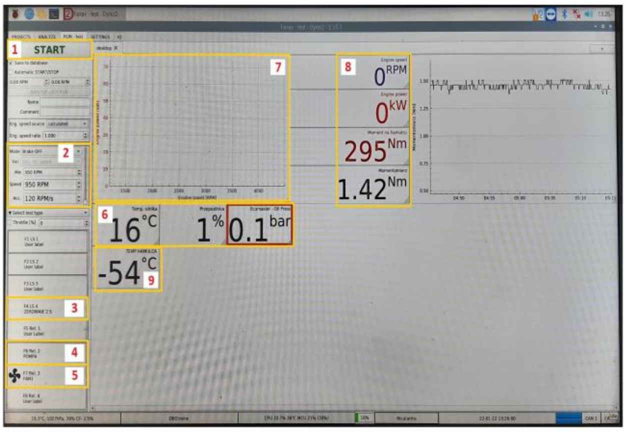

Fig. 2. Performance parameters of the hybrid set analyzed on the test stand: 1 – measurement start button, 2 – measurement mode selection, 3 – torque sensor setting to zero, 4 – water pump start button, 5 – cooling tower fan start button, 6 – ICE working parameters (temperature, throttle opening, oil pressure), 7 – characteristics chart, 8 – brake and torque sensor operating parameters, 9 – brake coolant temperature

The second concept is a two-cylinder boxer engine. In this arrangement, the two cylinders are placed on opposite sides of the crankshaft, creating a boxing-glove shape. These motors are known for their balance and smoothness, resulting in less vibration and noise. In addition, the low center of gravity of this type of engine can contribute to better vehicle stability.

The third concept is a V-twin engine. In this arrangement, the two cylinders are arranged in a "V" shape. This type of engine is often used in high-performance vehicles because it allows for a compact design while maintaining high power. The view of the dynamometer with the hybrid set for the two-cylinder V engine is shown in Fig. 3–5.

All three concepts were studied in terms of their potential use in a hybrid system, taking into account aspects such as performance, weight, size, cost and ease of use. The choice of the final concept was the result of careful consideration of these various factors.

Fig. 3. View of the connection system for 2 motors

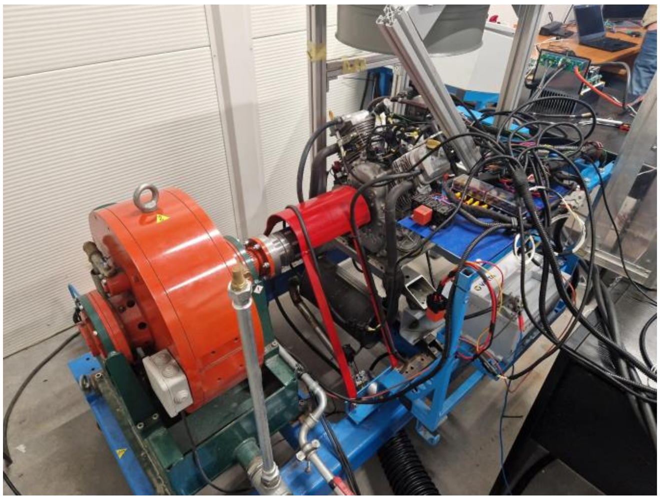

Fig. 4. View of the engine brake and drive set

The EMX-100/10000 brake was used in the tests. This brake is highly technical and is capable of absorbing a maximum power of up to 100 kW. It can achieve this at a maximum rotational speed of 10,000 revolutions per minute. From a mechanical point of view, the EMX-100/10000 is capable of generating a maximum torque of up to 240 Nm. From the design point of view, the brake has a weight of 250 kg, which proves its solid and durable construction. The direction of rotation of this brake is freewheeling, which adds flexibility to a variety of applications. However, it should be noted that the EMX-100/10000 requires a certain amount of water to function properly. The water requirement is 2.5 m³/h and the water pressure should be between 0.75 and 1.25 bar. The temperature of the water that is fed to the brake should be more than 30ºC for optimal performance. Finally, it is worth noting that the measuring arm length of this brake model is 0.370 meters. These precise measurements are essential to guarantee the highest quality of operation and performance.

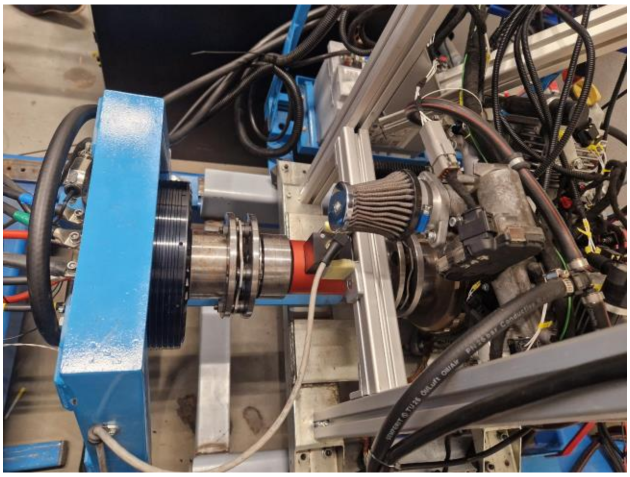

Fig. 5. View of a used electric motor and its connection

The dynamometer controller plays a key role in supervising and controlling the dynamometer operation (Fig. 6–7).

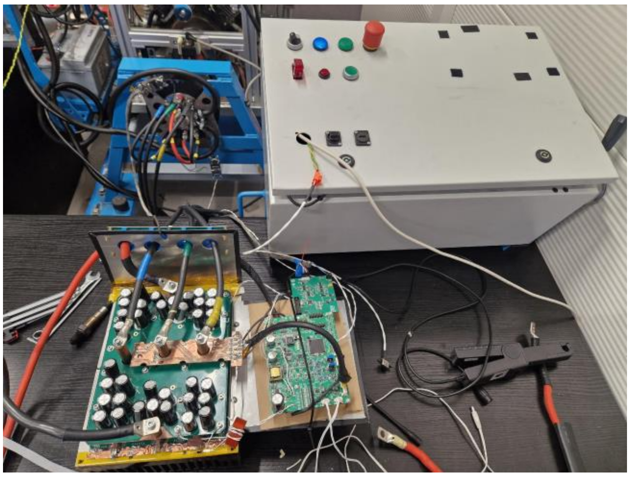

Fig. 6. Control and measurement system assembly – hybrid assembly dynamometer

Its operation covers a wide range of functions that allow effective and precise testing and diagnostic processes. The most important functions performed by the dynamometer controller are: Reading the dynamometer operating parameters and data from additional sensors. This allows continuous monitoring of the device status and current operating conditions. Generating a signal controlling the brakes of the load dynamometer. Thanks to this, the controller has a direct impact on the braking process. Control of dyno-associated accessories, such as fans. This allows to optimize the working conditions of the dynamometer and ensures proper cooling of the devices. Saving data and their subsequent analysis.

Fig. 7. Control and measurement system assembly – electric motor

Thanks to this, it is possible to track the history of the dynamometer's work, as well as identify possible problems and trends. Possibility of extending the functionality via CAN-BUS. This gives the possibility of integration controller with other systems and devices. In terms of input/output interfaces, the dynamometer controller is equipped with many connectors and ports that enable various forms of communication. Among them are Wifi, Bluetooth 5.0, Gigabit Ethernet, USB and microHDMI ports, mini jack audio connector and environmental sensor. An important element are also CAN-BUS 2.0B interfaces, various power outputs, analog outputs, PWM outputs, relay outputs, as well as inputs for speed and engine speed sensors and inputs for signals from strain gauges, general purpose analog inputs, thermocouple inputs and inputs for control buttons.

3.3. The electric motor used in the prototype

The EMRAX 208 electric motor is an advanced device used in hybrid systems. It is characterized by compact dimensions with a diameter of 208 mm and a length of 85 mm. The engine weighs between 9.4 and 10.3 kg and can be cooled by air, water or a combination of both. The motor peak power is 86 kW and the continuous power is 56 kW. The motor generates a peak torque of 150 Nm and a continuous torque of 90 Nm. Its maximum rotation speed is 7000 rpm, and the operating voltage can be from 50 to 580 V. The high efficiency of the EMRAX 208 motor reaches up to 96% (Fig. 8).

This motor is equipped with a position sensor, which can be either a resolver or an encoder, which enables precise monitoring of the position of the rotor. The EMRAX 208 electric motor offers significant power and torque while maintaining compact dimensions. Its high energy efficiency and a choice of different cooling methods make it a versatile solution for applications in hybrid systems.

So far, a number of significant activities have been carried out to develop and improve the hybrid drive. One of the key areas of work was the construction of the converter, which was based on the latest semiconductor switching elements and soft switching technology with increasing the operating frequency. The use of these advanced solutions allowed to reduce the weight of the converter and ensure high efficiency of energy conversion.

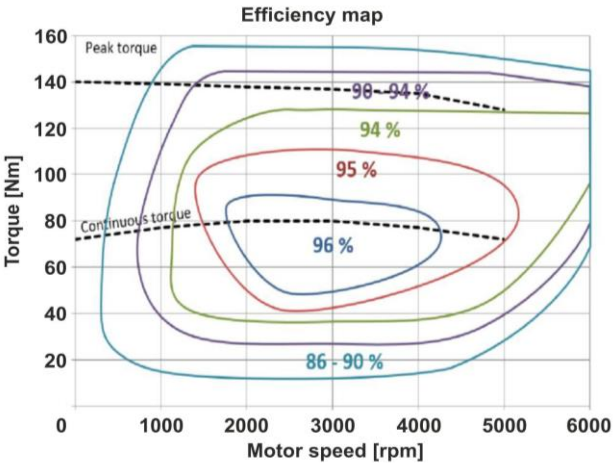

Fig. 8. Torque and speed motor characteristics – EMRAX 208

The control system uses the most modern DSP signal processors, which enable fast data processing and precise control. Active interference filtering systems and adaptive filtering algorithms have also been introduced, which significantly improve the quality of control signals. This allowed the implementation of complex vector control algorithms with a sinusoidal output current waveform, which in turn enables effective engine operation in a wide range of power and rotational speeds.

As part of the construction of the inverter, modern switching elements in SiC (silicon carbide) or GaN (threaded jelly) technologies were used, which replaced the previously used IGBT or MOSFET transistors. Soft switching technology was also used along with increasing the operating frequency of the inverter system. The latest generation DSP signal processors were used, which are responsible for real-time engine control algorithms. Back-EMF voltage measurement systems with a wide range and high measurement dynamics as well as active interference filtration systems and adaptive filtering algorithms have also been developed.

The control of the hybrid drive is based on a central supervisory system that coordinates the operation of the combustion and electric parts. Thanks to dedicated methods and algorithms for synchronization and power distribution, it is possible to achieve redundant operation of internal combustion and electric motors. This solution allows to increase flight safety, and also allows the drive to be adapted to various functionalities by changing the software. In the case of aircraft, it is possible to individually adjust the drive to the aerodynamic characteristics of the aircraft. The activities carried out are aimed at ensuring not only the efficient and effective operation of the hybrid drive, but also increasing its reliability and safety. The redundancy of the combustion and electric motors and the possibility of dynamic power sharing between them gives greater confidence that the drive will continue to function in the event of a failure of one of the parts. Additionally, an introduction dedicated synchronization methods allows for smooth and harmonious interaction of both motors, minimizing energy losses and optimizing their efficiency.

In the context of aircraft, adapting the hybrid drive to individual aerodynamic characteristics is extremely important. Thanks to the possibility of changing the software, it is possible to adapt the operating parameters of the engines and the way they are controlled to a specific vessel, ensuring optimal performance and efficiency. This, in turn, contributes to increasing the economic efficiency of the flight and reducing emissions. Conclusions from the conducted activities indicate significant progress in the field of hybrid drives. The use of advanced technologies and innovative solutions allows for the creation of high-efficiency electric motors. Optimization of both the construction of the converter and the controller enables effective management of the hybrid drive, increasing its reliability, safety and functionality.

It should be emphasized that the developed methods and solutions are a significant contribution to the development of hybrid drive technology, both in the context of aviation and other fields of transport. Their use allows for the effective use of various energy sources, reduction of pollutant emissions and achievement of better operating parameters. Further research and development in this area has the potential to lead to a revolution in propulsion, contributing to more sustainable and efficient transport.

3.4. Control system for the prototype engine and test stand

The main converter is a bi-directional converter that allows energy to flow to and from the batteries. The converter also determines the operating state of the internal combustion engine. This solution requires a specific design of the electronic controller of the internal combustion engine. Due to the generally accepted standards for aviation, the internal combustion engine controller was built as two independent units. The first unit is responsible for the value of the fuel injection parameter, and the second for the parameterization of the ignition sequence.

All three controllers – the main converter, the injection controller and the ignition controller are connected by a common CAN bus. Finally, a two-controller concept was adopted to control the hybrid drive system.

Injection electronic control unit

The electronic unit controlling the operation of the internal combustion engine is designed to generate the appropriate impulses to stimulate the injectors on the basis of strictly specific input signals. The inputs for such a signal are:

1) RPM – hall effect engine speed sensor, informing at the same time about the location of the first cylinder TDC
2) TPS – potentiometric throttle position sensor, indicating the "intent" of the pilot
3) MAP – air pressure sensor in the intake pipes
4) MAT – air temperature sensor in the intake pipes
5) FPT – fuel temperature and pressure sensor, in the fuel manifold.

Based on signals from the above sensors the dose of fuel applicable in the next one is determined.

The experimental injection control unit is based on the Texas Instruments RM48L540DPGETR DSP processor (Fig. 9). The injection sequence is built on the basis of input signals from the sensors. The injectors are controlled by current keys made in MOSFET technology. The injection control algorithm takes into account both the static states of engine operation – needed to determine the characteristic ones operating points and testing the possibility of replacing the generated mechanical power with electric power generated by the electric part of the hybrid unit. The injection controller PCB is shown below.

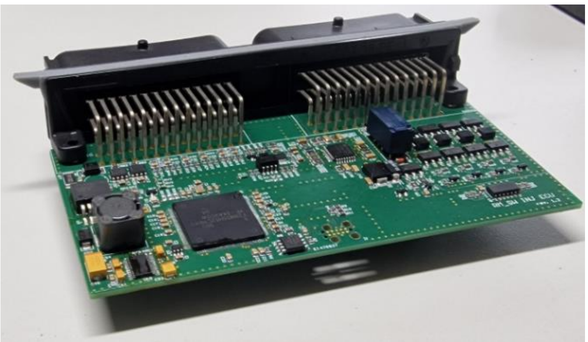

Fig. 9. Injection ECU – PCB view

Sample measurements of the generated sequence are shown below (Fig. 10). The yellow line shows the pulses coming from the rotation sensor. The orange line and the red line represent injector control for the first and second cylinders, respectively. Later in the post-start waveform, a phase shift sequence is observed for both cylinders.

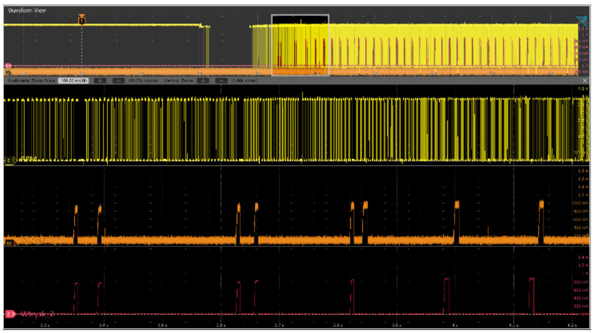

Fig. 10. An example of a sequence of injection pulses The first two pulses after the rotational speed occur are caused by fuel injection and facilitating engine start-up

The first two pulses after the onset of rotational speed are caused by the fuel injection and engine start facilitation. Later in the post-start waveform, a phase shift sequence is observed for both cylinders.

The ignition coil control sequences are shown below (Fig. 11).

The waveform from the rpm sensor is marked with a yellow line. The orange and red lines show the ramming of the ignition coils.

The angular displacement between both cylinders of the controlled internal combustion engine is clearly visible. The duration of the control pulse depends on the supply voltage and the falling edge causes a physical spark in the engine cylinder.

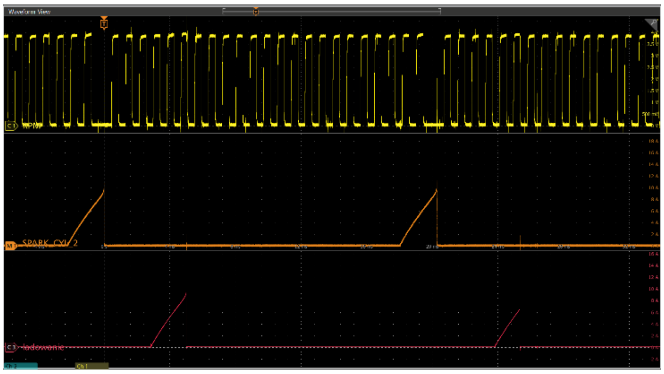

Fig. 11. Circuit layout sequence

4. Preliminary research results and discussion

As a result of the tests carried out on the combustion engine dynamometer and the comparison of the measurement results with the electric and combustion drive, it was found that there is no significant wear of the main engine components and engine timing. These studies allowed for a thorough examination of the resistance to motion of the hybrid set depending on the rotational speed of the internal combustion engine.

The results showed that after connecting the electric motor to the hybrid set, the resistance to motion increased by 8 to 17%, depending on the rotational speed of the internal combustion engine. Additional drag is also dependent on the angular velocity of the propeller and aerodynamic drag, and its value ranges from 5 to 23% (Fig. 12).

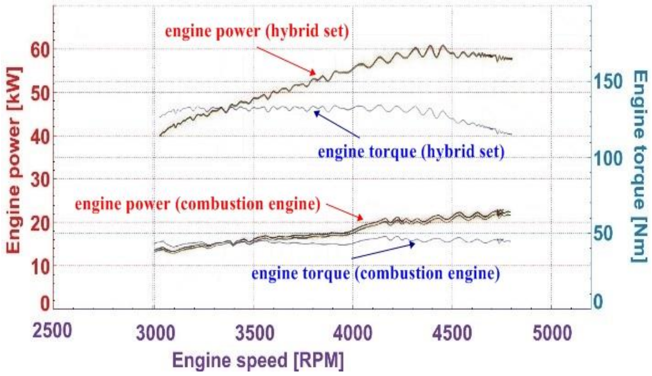

Fig. 12. Course of power and torque of the internal combustion engine and hybrid drive: torque [Nm], useful power [kW]

The resistance to movement of the combustion engine and electric motor drive set was calculated according to a specific scheme. Measurement of the engine torque in the full range of its rotational speed at the oil temperature of 90°C and 110°C. These data allowed to determine the characteristics of the moment of resistance to the movement of the internal combustion engine. A high-class torque meter placed between the internal combustion engine and the electric drive motor was used for the tests. The rotational speed of the internal combustion engine was regulated by means of the rotational speed of the electric motor controlled by the inverter. The measurement was performed at a constant oil temperature for a given rotational speed. The measurement was carried out every 250 rpm. In order to determine changes in the resistance to motion of the electric motor of the hybrid set, an electric motor was connected to the internal combustion engine. Then the measurement was carried out in a similar way as for the internal combustion engine. In the case of determining the resistance to motion of the hybrid set with the propeller connected, the author's dynamometer was used an aircraft engine from Świątek. In this case, changes in the torque of the internal combustion engine and electric motor in relation to this set with the motor connected were determined. The percentages given are ranges for the resistance moment variation of the assembly in these configurations.

These results indicate a significant impact of the electric drive on the resistance to motion of the entire hybrid system. However, it is worth noting that these values are acceptable and do not adversely affect the performance of the hybrid assembly. In addition, the increase in drag is related to additional factors, such as the angular velocity of the propeller and aerodynamic drag, which are natural factors that occur during the flight of an airplane.

A hybrid system in which an electric motor works in conjunction with an internal combustion engine can be an effective solution for hybrid aircraft, enabling significant reductions in fuel consumption and emissions. However, further research is worthwhile to further determine the effect of drag on the efficiency and range of such hybrid aircraft.

The increase in engine motion resistance in the case of a hybrid set results from several factors. First of all, connecting the electric motor to the combustion system introduces additional mechanical elements, such as gears, clutches or other elements connecting the motors. These elements introduce some energy losses due to friction, which leads to an increase in the resistance to motion.

In addition, the electric motor can affect the operation of the internal combustion engine by changing the load characteristics. For example, during hybrid drive operation, the internal combustion engine may be loaded to a greater extent to provide adequate power for the operation of the electric motor, or vice versa, when the electric motor assists the internal combustion engine. This extra load can lead to an increase in the motor's resistance to motion. In addition, the increase in the resistance to motion may also be related to the dynamic effects of the electric motor, such as the moment of inertia of the rotor, aerodynamic drag of the propeller or the influence of electronic control on the operation of the motor. These factors can cause additional energy losses and increase the resistance to motion in the hybrid assembly.

A conventional internal combustion engine, when loaded with a propeller, has a net power of 23 kW at 4750 revolutions per minute (rpm), reaching a maximum torque of approximately 48 Nm. On the other hand, the newly proposed hybrid drive system, combining an internal combustion engine and an electric motor, shows much better parameters. The useful power of the system is 61 kW at 4400 rpm, and the maximum torque is as much as 135 Nm, available over a wide speed range, from 3100 to 4400 rpm. Such a significant improvement in parameters allows for greater operational flexibility of the powertrain. The spread of the rotational speed is wider, which allows better adaptation to the variable speed of the propeller. In addition, it maintains high torque over a wide range of engine speeds, which is particularly advantageous in a variety of flight conditions. The use of a hybrid drive system, as the above data shows, brings decisive benefits in in the context of energy efficiency and operational flexibility. This confirms the innovativeness of the propulsion unit proposed in this work and indicates its potential in further research and development of ultralight aircraft technology.

The parameters of the electric motor play an important role in the case of its independent operation and in combination with an internal combustion engine. In both cases, the electric motor must overcome the additional resistance to the movement of the main engine mechanism and the propeller drive, which generates friction losses and affects the efficiency of the entire system.

When operating an electric motor in a hybrid set, key parameters such as inverter temperature (hb_{temp_C}), electric motor current ($iq_{\_A}$) and inverter input power ($power_{\_P}$) have a significant impact on its efficiency. When transferring energy from the battery to the electric motor, the current ($battery_{Current\_A}$) and battery voltage ($battery_{Voltage\_V}$) play an important role in ensuring adequate power and efficiency.

In addition, the rotational speed of the motor ($speed_{\_rpm}$) is a key parameter that affects the efficiency of the electric motor and the resistance to movement it must overcome. The higher the rotational speed, the greater the resistance to movement and the greater the friction losses. It is worth noting that the efficiency of the electric motor in the hybrid set may be reduced due to the additional load and energy losses resulting from overcoming the resistance to the movement of the main engine mechanism and the propeller drive. Therefore, it is important to properly adjust the parameters of the electric motor and optimize the control in order to minimize these losses and ensure the highest efficiency of the hybrid system.

In Fig. 13, an increase in the power of the electric motor can be observed during the simulated take-off of the aircraft. According to this drawing, the maximum power with an average load of the propeller system and the internal combustion engine for the electric motor is from 40 to 43 kW. The power change is caused by the change in the engine speed in the hybrid set with the simultaneous application of a medium load with the propeller connected. The test was carried out on a dynamometer. This is a very large increase in power, which is particularly important for quickly gaining altitude, but also for safety. The voltage drop on the hybrid set battery in this period is shown in Fig. 14. Figure 13 shows a graph of electric motor power in the full range of rotational speed. The results indicate the possibility of obtaining maximum power by the electric motor. The impact of the use of a hybrid propulsion system of an ultralight aircraft mainly influenced the increase in the torque and power of the propulsion system. The electric motor allows to increase the power and torque in key moments of the aircraft's operation, i.e. the period of take-off, landing and possible aerobatic maneuvers adapted to the structural strength of the aircraft. This system primarily improves the take-off conditions of the aircraft and provides protection in the event of a combustion engine failure. This set, together with the assumed capacity of the batteries, allows for a safe flight of the aircraft for several minutes only with the use of an electric motor. This allows you to avoid a plane crash and safely land a damaged aircraft without internal combustion engine. It is a fairly simple concept in the connection system of the internal combustion engine and the electric motor, which guarantees increased safety and a lower probability of drivetrain failure.

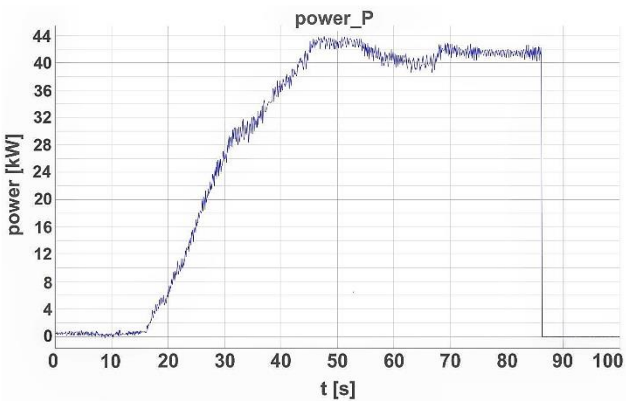

Fig. 13. Change of electric motor power in series connection with medium propeller load

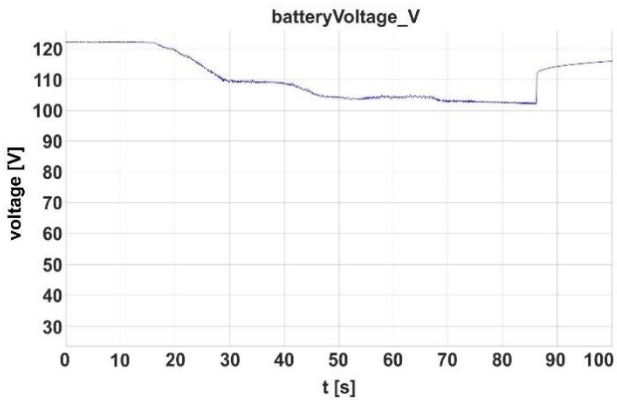

Fig. 14. Voltage drop on the battery cells of the hybrid set

Figure 15 shows the increase in the current value of the battery cells. The maximum value is 410 A. This value does not damage the battery and is a safe value. The current value analogously corresponds to the power increase of the electric motor.

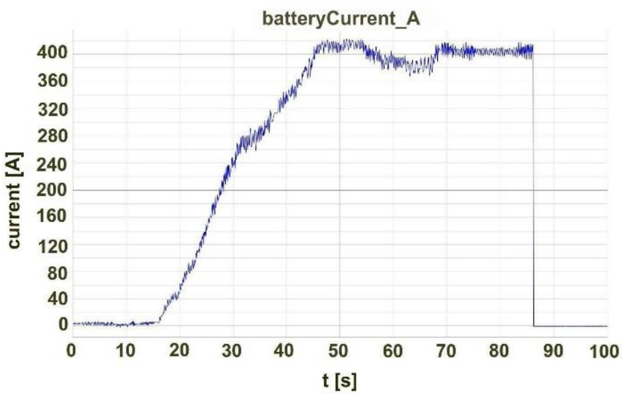

Fig. 15. Change of the current in the battery cells during the period of increasing the power of the electric motor

Similarly, Fig. 16 shows the change in the current value of the electric motor. This is an acceptable value and does not constitute a basis for damage to the electric motor during a sudden increase in the power demand of the hybrid set.

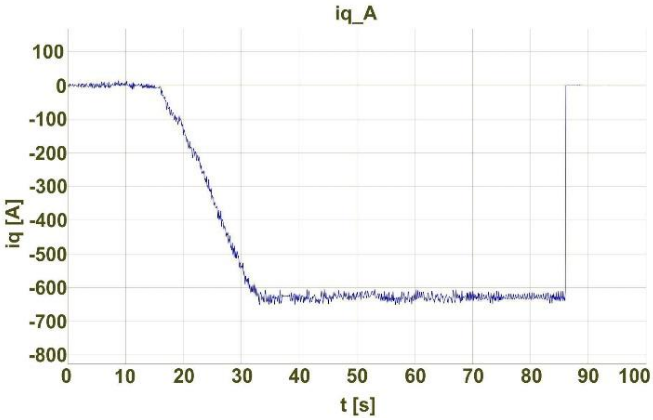

Fig. 16. Change of the current value in the electric motor

The rotational speed of the electric motor is shown in Fig. 17. The average usable range of the rotational speed of the motor shaft is in the range from 2850 to 4800 rpm. The electric motor can have different power ranges depending on the rotational speed. Appropriate adjustment of the rotational speed to the required power allows you to achieve the optimal combination of efficiency and vehicle performance.

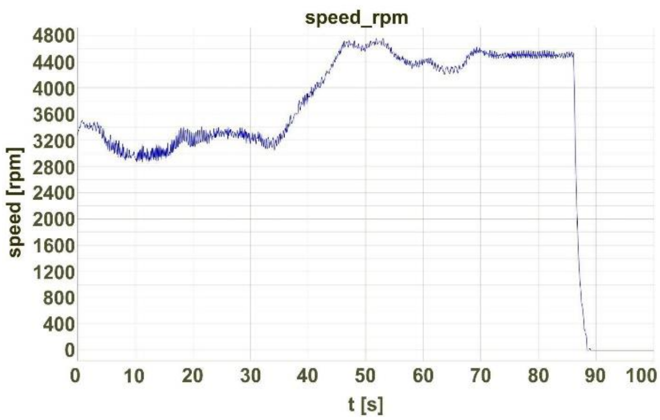

Fig. 17. The rotational speed of the electric motor for given operating conditions

For example, when accelerating or climbing hills, the high rpm of the electric motor can deliver more power, resulting in better performance. The rotational speed of an electric motor affects its energy efficiency. Electric motors are most efficient within a certain speed range, known as the optimum operating point. By operating near this point, the motor uses less electricity per unit of work done. The rotational speed of the electric motor also affects the torque it generates. Torque is the force that causes the drive shaft to rotate. In a hybrid system, the electric motor often supports the internal combustion engine. When accelerating a vehicle, the electric motor can deliver more torque than the combustion engine at low revs, allowing for quicker and smoother acceleration.

Figure 18 shows the waveform of the inverter temperature at the moment of engine load in terms of its rotational speed and the achieved power. The temperature value in this period reached a maximum level of about 46°C. Then, when the engine was turned off, the temperature decreased rapidly. This proves that during the motor overload period, in order to achieve the appropriate power, there is no need to use additional cooling measures for the inverter, and there is no risk of its overheating.

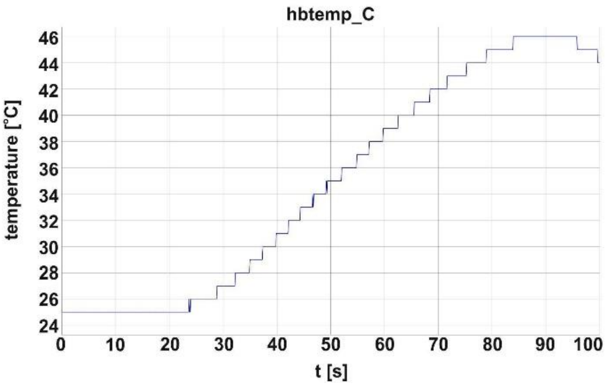

Fig. 18. The course of the inverter temperature at the time of electric motor operation

5. Summary

The work focuses on the design and research of an innovative propulsion unit for ultralight aircraft. It introduces a new approach to energy efficiency and operational flexibility, defined by a hybrid system that combines an internal combustion engine and an electric motor/generator. Key elements of this innovation include an advanced internal combustion engine controller and a bi-directional energy conversion converter, allowing the two energy sources to work together optimally. In addition, a special test stand was developed and built to carry out tests on the prototype of the drive unit.

The results of these tests, in the form of initial prototype performance characteristics and performance analysis, suggest the potential benefits of using such a hybrid drive unit.

The work also contains conclusions and recommendations for further work on improving this innovative technology. All this, combined, makes the presented work a significant step forward in the field of energy efficiency and operational flexibility of ultralight aircraft, and thus shows a significant degree of innovation.

The most important conclusions from the work are:

- The use of a hybrid propulsion system in accordance with the proposed design allows for achieving excellent operational parameters, increasing power and torque during take-off of the aircraft. This not only improves flight performance but also increases safety.
- The maximum value is 410 A. This value does not damage the battery and is a safe value. The results showed that after connecting the electric motor to the hybrid set, the resistance to motion increased from 8 to 17%, depending on the rotational speed of the internal combustion engine. Percentage differences in motion resistance result from changes in the rotational speed of the internal combustion engine shaft. To a large extent, the value of the resistance depends on the resistance of the electric motor and the internal combustion engine. In the case of an internal combustion engine, the resistance to motion depends on the lubrication parameters, and in the case of an electric motor, on the resistance of its bearings. Additional drag is also dependent on the angular velocity of the propeller and aerodynamic drag, and its value ranges from 5 to 23%. Aerodynamic drag was adopted on the basis of data from aircraft flight parameters for a given flight speed. This is also due to the angle of inclination of the propeller blades. It is assumed that a given airspeed is obtained for given engine speeds. This, in turn, can be compared in a general way to the aerodynamic drag calculated theoretically.
- The electric motor reaches its maximum power during the tests from 40 to 43 kW, in the range from 2850 to 4800 rpm, with the maximum temperature of the inverter not exceeding 46°C.
- In the classic system, the internal combustion engine alone, when loaded with the propeller, achieved a useful power of about 23 kW at 4750 rpm, the maximum torque is about 50 Nm. In the hybrid connection, the net power of the set is 61 kW at 4400 rpm, the maximum torque is approximately 135 Nm over a wide range from 3100 to 4400 rpm. As a result, the hybrid set has a wider range of useful rotational speeds and is easier to adapt to the variable speed of the propeller. This gives the propeller greater flexibility while maintaining high torque in a wide range of rotational speed of the drive set.
- The implementation of the energy control system enabled effective management of both the combustion engine and the electric motor, which resulted in optimal use of the available power. This innovation can lead to significant fuel savings and overall propulsion efficiency over a wide range of operating conditions.

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Project carried out as part of the competition of the National Center for Research and Development: Fast Track. POIR.01.01.01-00-1304/19.

Nomenclature

hb_{temp_C}	inverter temperature	$battery_{Current\_A}$	battery current
i_{q_A}	electric motor current	$battery_{Voltage\_V}$	battery voltage
$power_{\_P}$	inverter input power	$speed_{\_rpm}$	engine speed
t	time		

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