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HYBRID GAS-ELECTRIC MULTI-ENGINE TESTBED – RESULTS OF THE RESEARCH

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Abstract

The significant increase of interest in the green aviation, therefore in the alternative propulsion systems is surely caused by the concern for the environment but mainly due to limitations and restrictions arising from declarations and legal acts of governments and aviation institutions. The main impact of reducing the greenhouse gasses emission is expected to be achieved in the civil aviation since the constant growth of the air traffic passenger demand. Even though many well-known companies, small start-ups as well as great consortiums attempt to design, create, test and certify at least a regional hybrid gas-electric aircraft, which is one of many examined environment-friendly ideas, projects face many issues such as: insufficient technology of batteries, complicated design of a Power Management Unit, necessity of applying a complex cryogenic cooling system as well as safety reasons. Currently the technology of the hybrid gas-electric propulsion system, where the thrust is produced by electric engines with fans/ propellers, which are driven by the Internal Combustion Engine is available only for small aircraft, mainly with a single motor. For this reason, the WUT team decided to gain knowledge regarding the hybrid gas-electric multi-engine solution and adapt this kind of propulsion system to one of the Warsaw University of Technology gliders. The main objective of this paper is to present results of the test campaign conducted on the hybrid gas-electric multi-engine testbed which was designed and tested to demonstrate feasibility of such a propulsion system for the existing two-seat aerobatic glider named PW6. The positive results of ground tests could lead to implementation of the propulsion system to the glider and then be tested in-flight.

Keywords: hybrid, gas-electric, multi-engine, testbed, results of research, green aviation

Abreviations:

ECU – electronic control unit

ICE – Internal Combustion Engine

1. Introduction

The pursuit to be a pioneer in finding the green solution for the future civil aviation continues as the international institutions and government organizations build up the pressure to reduce the emission of greenhouse gases by whole industry. What was started by the ICAO CORSIA [1] plan (Carbon Offsetting and Reduction Scheme for the International Aviation) and N+3 NASA program [2], now it is continued by European Green Deal [3] and United States Aviation Climate Action Plan [4]. The definition of these programs differ, however the main idea is the same: cut the Carbon Dioxide emission in aviation sector in any possible way.

Different projects of which "Clean Sky 2" [5] and Boeing Subsonic Ultra Green Aircraft Research [6],

[7] are the greatest, considered different alternative solutions. Brainstorming conducted by different companies and consortiums led to a few mainly considered alternative solutions: all-electric, hybrid-electric (hydrogen or gas fueled) or turboelectric. The most promising in terms of reduction of greenhouse gases emission is the all-electric solution. Unfortunately, current technology is not able to provide batteries with so high specific energy to allow this type of propulsion to be used in long-range heavy aircraft. It is rather used for small aircrafts as Lilium VTOL [8]. However, it is believed that with the specific energy of 600-700 Wh/kg Lithium-Sulphur batteries can replace Lithium-Ion batteries in the near future [9]

The less sensitive for the battery status is the turboelectric solution, since the usage of batteries in this application is not necessary (but possible) [10]. This propulsion assumes common work of many electric motors (often in a distributed form) directly driven by the turboshaft engine. It is represented by two main configurations: full and partial turboelectric. The turboelectric propulsion appears to be the most promising for the large aircraft e.g. NASA STARC-ABL [11].

Assuming development of battery technology, for the commuter and regional transportation hybrid gas-electric solution tends to be the best alternative, since it utilizes advances of both electric engine and the ICE, meanwhile the disadvantages are minimized. Optimal operation hence lower fuel consumption of the ICE and recharging batteries during the flight help to achieve reduction of the CO_2 emission. On the other hand, long range flight is possible due to high specific energy of fossil fuels, compared to all-electric aircraft. Often as advantages of this solution downsizing of the ICE or redundancy of energy sources are mentioned, but a lot more can be found in [12].

2. Testbed

The research was conducted on the ground testbed, which was designed for the PW6 two-seat glider in the aerobatic configuration. The design was performed in such manner that as less as possible adjustments in aircraft’s structure had to be made in order to install the hybrid propulsion system in the standard configuration of the structure. The idea was to mount two electric motors with propellers behind the trailing edge of the wing, two sets of batteries in the nacelles in front of the leading edge in line with motors and the generator set (including an ICE and an electric motor as a power generator) at the top of the fuselage. ICE was envisaged to work with constant RPMs referring to maximum value of power to fuel consumption ratio. Output of the generator should provide positive climb rate. In the case of horizontal cruising, excess of power would be used to charge batteries. On the other hand, batteries would supply additional power necessary to perform takeoff and large initial climbing to safe altitude.

After many design steps, which were thoroughly described in [13] the following components of the testbed were chosen:

- Hirth 3503 (two-cylinder in-line, two-stroke) as the ICE combined with the PMSM EMRAX 268 motor (water-cooled, low-voltage) as the power generator.
- Gearbox matching maximum RPM-s of the ICE with maximum efficiency RPM-s of EMRAX 268.
- Two PMSM EMRAX 228 motors (air-cooled, high-voltage) to drive two or three blade propellers of 1,3 m diameter, allowing for pitch adjustments.
- A power supply instead of battery set to be tested on the ground (to enable measurement during ground tests).
- HV-500 inverters: air-cooled for propellers and liquid-cooled for the power generator.
- A control unit: a single-board computer running the Linux operating system with the CAN interface.

The simplified architecture of the designed ground testbed is presented in the Fig. 1, whereas in the Fig. 2 the ground testbed in operation is shown.

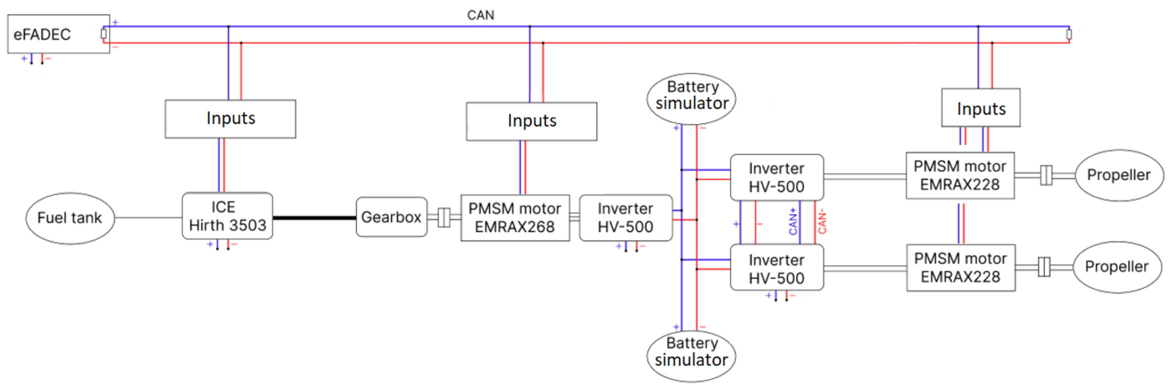

Fig. 1 The simplified architecture of the propulsion system ground testbed.

Fig. 2 The ground testbed of the propulsion system.

3. Methods of research

Thanks to the built-in PID controller, it is possible to control the described testbed by two different operating modes:

- Maintaining requested RPM,
- Maintaining requested current (equivalent to torque) of the electric motors.

Both operating modes were tested during the research.
Two main aspects of the hybrid gas-electric propulsion testbed were examined. The first one applies to the common work of the chosen Emrax 228 electric motor and the two and three blade propellers. The goal was to obtain aerodynamic characteristics of the propellers and determine the optimal operating point of the propeller driven by the motor.
The propeller performance evaluation was conducted utilizing such components of the testbed: the

Emrax 228 electric motor, the two and three blade propellers, the power supply imitating the operation of the battery sets and the power generator. For smaller propeller pitch angles, the motor was supplied only from the power supply, for greater – from the power supply and the power generator.
The following variables were taken into account:

- Supply voltage: 360, 400, 440 V,
- Propeller pitch angles: 10, 15, 20, 25 degrees,
- Two operating modes: requested rotational speed or current (torque).

During the propeller performance evaluation following parameters were measured: torque, rotational speed, input voltage and motor’s current. Last two parameters enabled to calculate the consumed power by the electric motor therefore determine the optimal operation point were the thrust generated by the propeller was the greatest regarding to the power consumed by the electric motor. Due to the stationary design of the testbed, it was possible to measure only static thrust.
The second aspect which was considered refers to the power generator set consisting of the Hirth 3503 engine and the Emrax 268 electric motor, connected by the gearbox and the other necessary equipment (the cooling system, the exhaust system, converter etc.). The main goal of these studies was to create the map of the specific fuel consumption by the set in relation to the power generated and rotational speed. It was expected that optimal operating point (the maximal ratio of the generated power and the consumed fuel) should occur for some rotational speed range and opening of the throttle under certain load from generator.
The power generator’s performance evaluation was conducted utilizing the ICE, the electric motor in generator mode, one set of the electric motor and the propeller. In case of smaller power generated by the power generator, the current was feed back to the electric grid, in case of greater power – the current was partially supplying the electric motor driving the propeller.
The parameters were measured with respect to the following variables:

- Rotational speed of the electric motor (generator): 2000 – 6500 RPM with leap every 250 RPM,
- The ICE throttle opening: 15 – 100% with leap every 5%,
- Two operating modes: requested rotational speed or (current) torque of the electric motor (generator).

The power generator’s performance study included measuring of the rotational speed of the ICE, the fuel consumption and the power generated by the generator set.

4. Results of research

Propellers’ performance evaluation included verification of thrust vs rotational speed curves for different pitch angles and different supply voltage. These curves are usually used to determine the pitch angle required to produce determined thrust, which depends on the required power thus flight parameters such as velocity, climbing velocity, mass of the aircraft, flight altitude, etc. In the case of current research, it was also important to match propellers settings with the generator output in the most economical way. In this case, it was necessary to verify not only thrust vs rotational speed curves (Fig. 3 a, c, e for the 2-blade propeller and Fig. 4 a, c, e for the 3-blade propeller) but also thrust/ consumed power vs rotational speed curves (Fig. 3 b, d, f for the 2-blade propeller and Fig. 4 b, d, f for the 3-blade propeller). The values presented on the graph are corrected due to the performed calibration of the equipment.
Undoubtedly, the greatest ratio of the thrust over the consumed power of about 0,05 N/W and 0,052 N/W (for the given two and three blade propeller respectively) is obtained for both propellers for the pitch angle of 15 deg. The optimal operating point is within the rotational speed range of about 1250-1500 RPM and 1000-1500 RPM for the two and three blade propeller respectively. For such an optimal operating point the produced thrust is up to 200 N (for the 2-blade propeller) and 250 N (for the 3-blade propeller) for the 1500 RPM regardless of the supply voltage. The supply voltage (for both 2 and 3-blade propeller considered separately) does have only small impact on the thrust vs rotational speed curves (Fig. 5a) and consumed power vs rotational speed graph (Fig. 5b), however it finally seams to have the slight impact on the thrust to consumed power ratio vs rotational speed

curves, especially for the small rotational speed (1000-1500 RPM) (Fig. 5c). But this is effect of calculating ratio of two small values burdened with measurement errors.

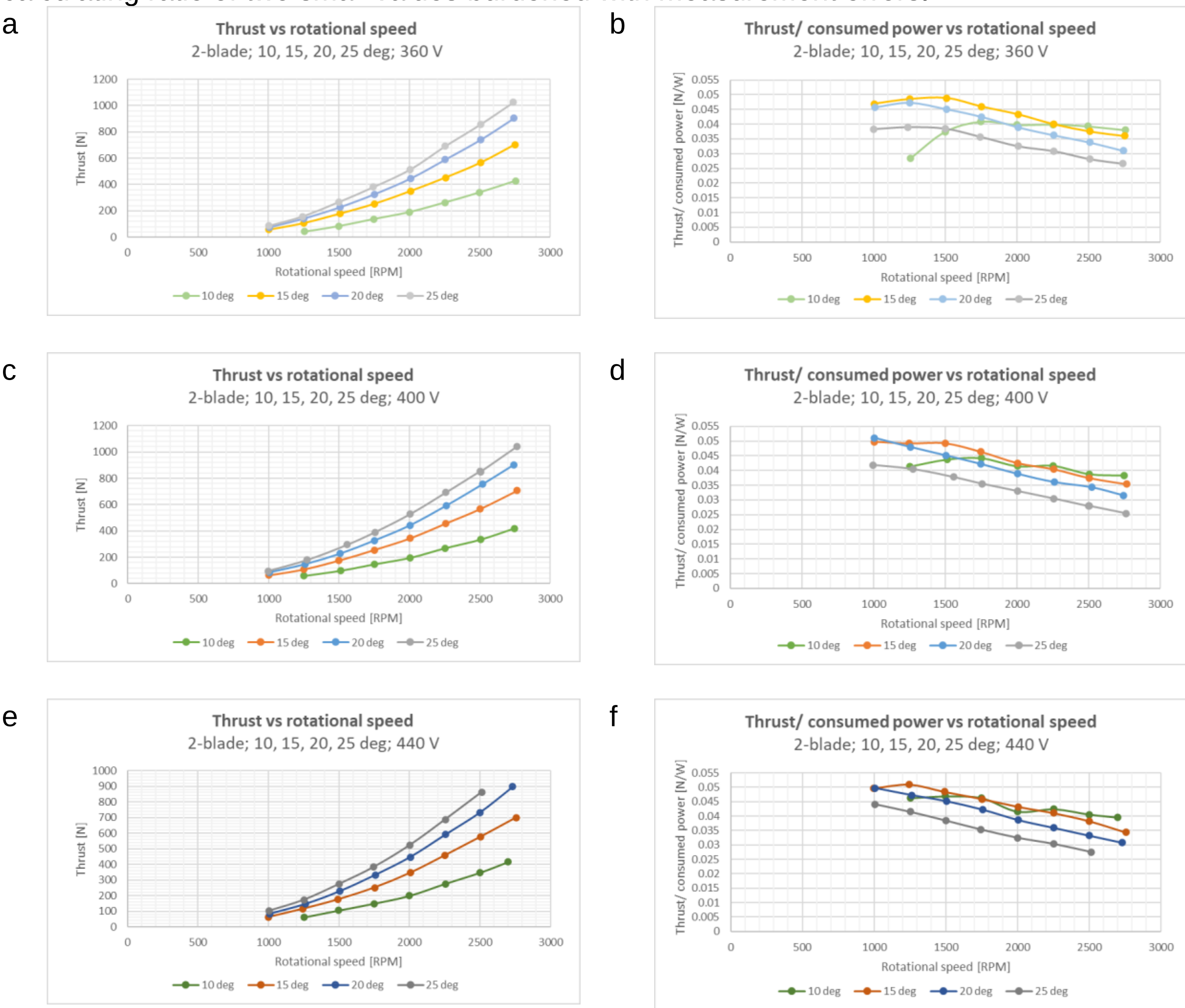

Fig. 3 The 2-blade propeller results: a) thrust vs rotational speed, 360 V, b) thrust/ consumed power vs rotational speed, 360 V, c) thrust vs rotational speed, 400 V, d) thrust/ consumed power vs rotational speed, 400 V, e) thrust vs rotational speed, 440 V, f) thrust/ consumed power vs rotational speed, 440 V.

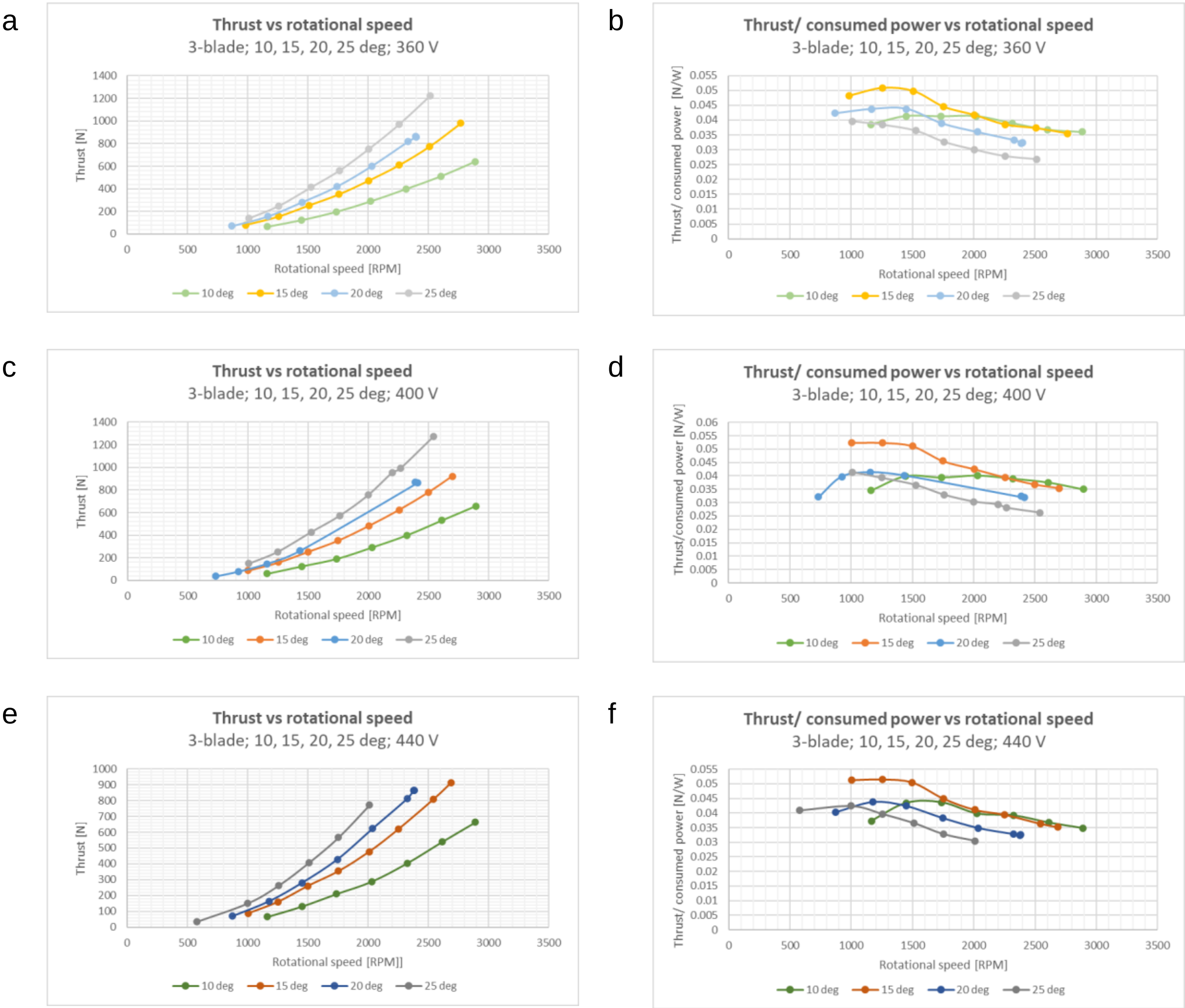

Fig. 4 The 3-blade propeller results: a) thrust vs rotational speed, 360 V, b) thrust/ consumed power vs rotational speed, 360 V, c) thrust vs rotational speed, 400 V, d) thrust/ consumed power vs rotational speed, 400 V, e) thrust vs rotational speed, 440 V, f) thrust/ consumed power vs rotational speed, 440 V.

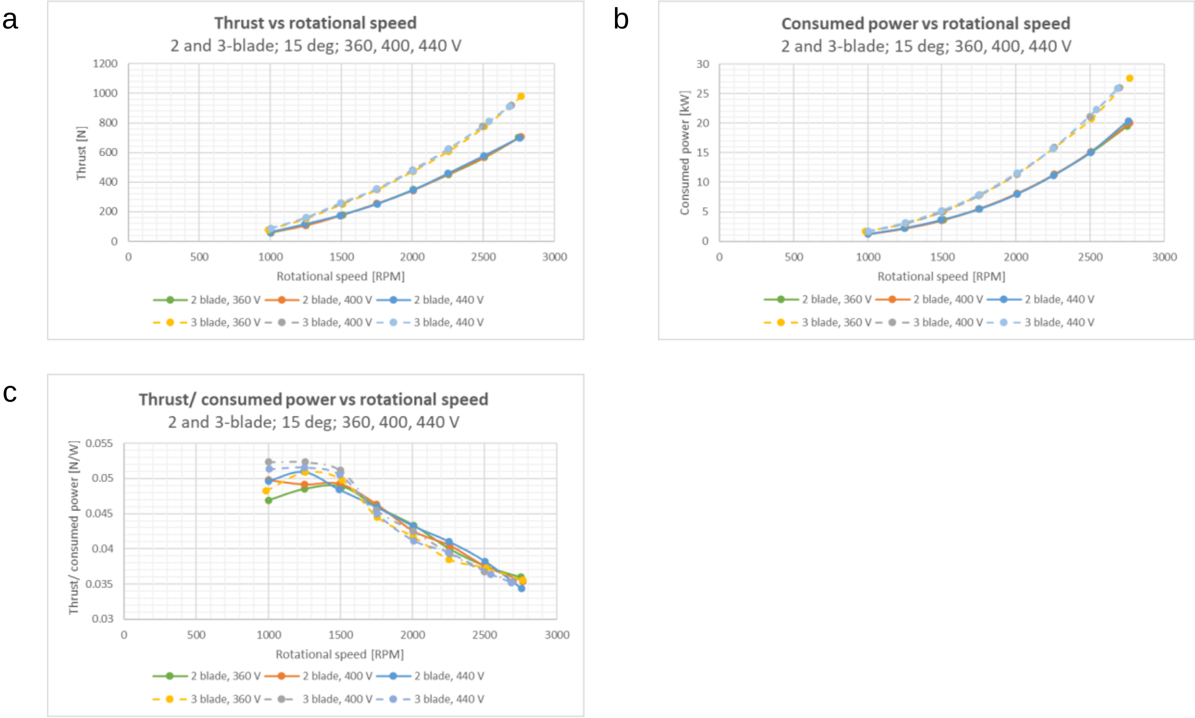

Fig. 5 The propeller results: a) thrust vs rotational speed, 2 and 3-blade, 15 deg, 360, 400, 440 V, b) consumed power vs rotational speed, 2 and 3-blade, 15 deg, 360, 400, 440 V c) thrust/ consumed power vs rotational speed, 2 and 3-blade, 15 deg, 360, 400, 440 V

The second aspect of the research concerning the hybrid propulsion system covered the common work of the Hirth 3503 ICE, gearbox and the Emrax 268 motor, together named the generator. The idea was to determine the optimal, continuous operating range at which the ratio of power generated to fuel consumption would be as high as possible. Therefore, the maps of the specific fuel consumption vs the opening of the throttle and the rotational speed (Fig. 6) and the specific fuel consumption vs the generated power and the rotational speed (Fig. 7) were created based on many measured average values of the operating points These points were interpolated and the estimated surfaces were created. Due to wide range of rotational speed the research was conducted in many days differ from each other. Problems with stabilizing the rotational speed of the power generator, issues with communication system, problems with gearbox and many others, made the map quite bumpy and rough. The surfaces were neither smoothed by a computer in order not to hide real data.
It can be noticed easily that, as expected, the peak of the maximum generated power over fuel consumption ratio occurs (Fig. 6). It happens for the rotational speed of 6000 RPM and the throttle opening of 65-95%. The generated power differs from 30 kW to 35 kW for the throttle opening equal to 65% and 95% respectively (Fig. 7). The optimal operating point for the throttle opening of 95% and the rotational speed of 6000 RPM is simultaneously the point with optimal generated power. As expected, the optimal power of 35 kW generated by the power generator differs substantially from the 51,5 kW of maximum power declared for the Hirth 3503 ICE. The gap is not only due to the difference between peak and optimal operation of the engine, but also because of losses caused by additional parts of the generator system (electric motor, gearbox etc.), not included in the engine data.
There is one operating point (for the rotational speed of 5750 RPM and the throttle opening of 90%) with higher maximum ratio of the generated power over the fuel consumption than described range of 6000 RPM (Fig. 6). However, it was omitted as an unreliable operating point since it significantly deviates from neighbouring points. It is going to be verified in further activities conducted at the testbed.

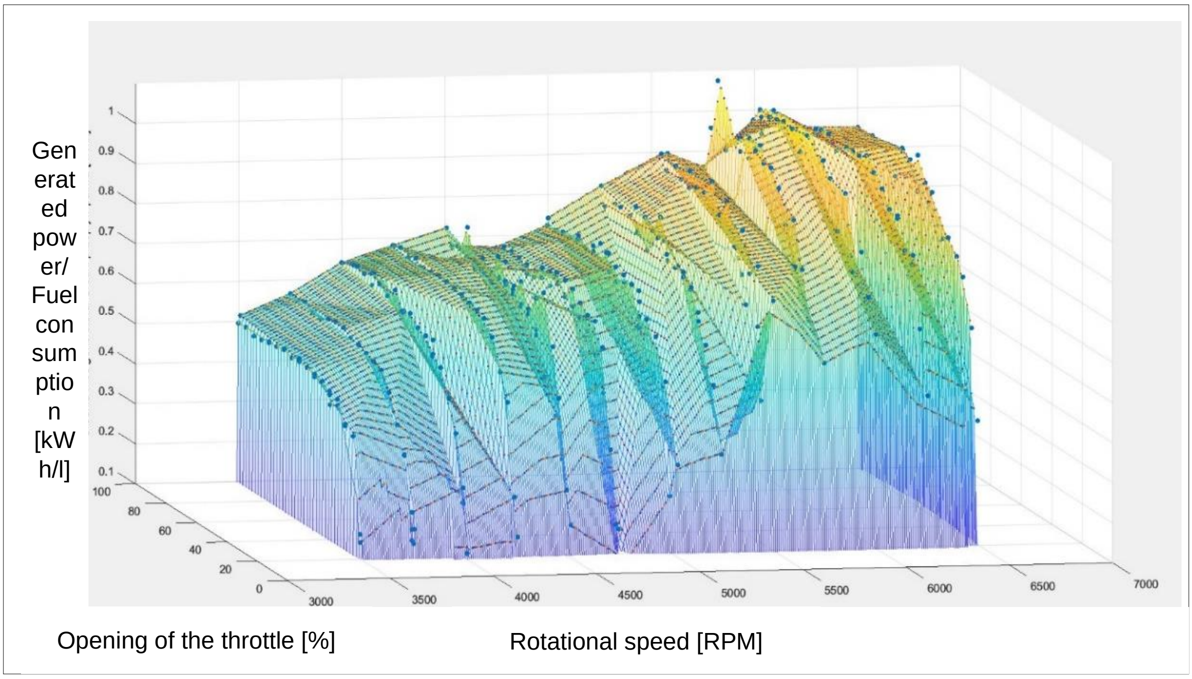

Fig. 6 The generated power/ fuel consumption vs the opening of the throttle and the rotational speed graph for the power generator

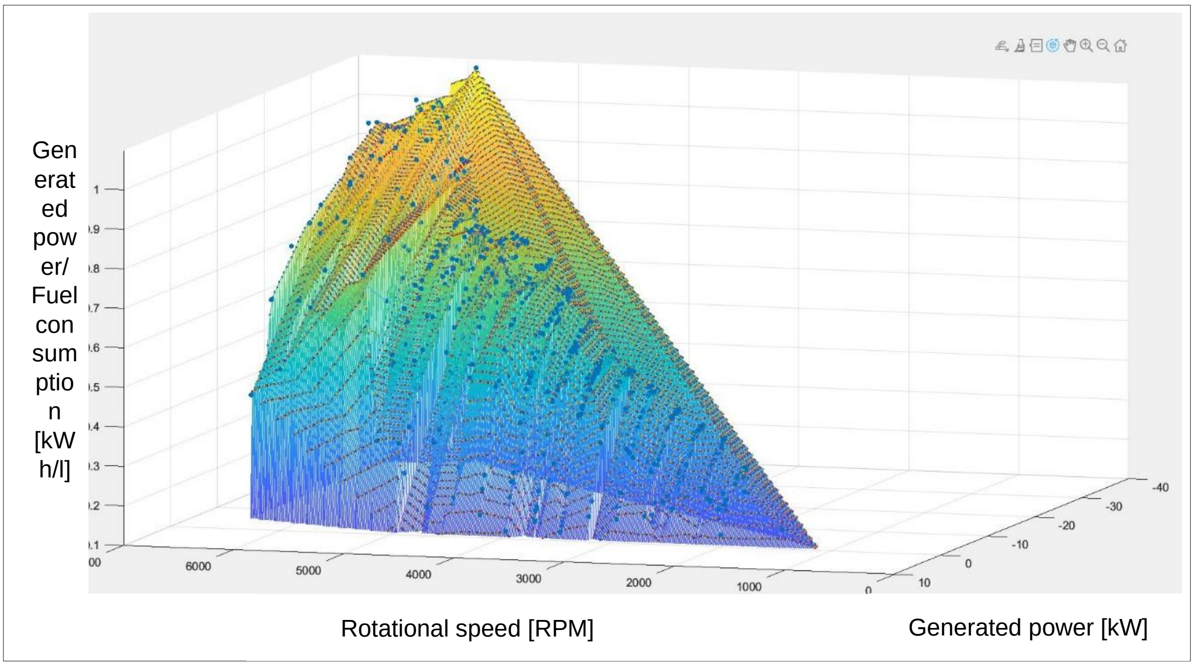

Fig. 7 The generated power/ fuel consumption vs the generated power and the rotational speed graph for the power generator

The obtained value of the optimal generated power of 35 kW is clearly the most promising point of generator's work. Adding to the optimal power of the generator the power of 20 kW which can be provided by two battery sets (see [13] the maximum power of the entire hybrid testbed equals to 55 kW, so maximum of 27,5 kW of power can be consumed by each Emrax 228 motor which drives the propeller to produce the thrust. At this point it is impossible to verify what performance can be achieved with this power, since the measurements were only static. Therefore, it is planned to calculate propeller's efficiency in an appropriate software as well as to conduct dynamic studies in the wind tunnel.

At this moment it is only possible to estimate the following static values of power delivered to each motor for each operational modes:

- ”Take-off”, when the power consumed by the motors driving each propeller is not greater than 27,5 kW (the ICE and batteries are the common energy source),
- “Climbing” with battery cooling, the power consumed by the motor driving each propeller does not exceed 17,5 kW (only ICE is the energy source),
- “Emergency” (the ICE failure), when the power consumed by the motor driving each propeller is equal to the power of one battery set (about 10 kW),
- “Cruise” – the power from ICE is used to fly (more than 5 kW - say 7 kW by each motor) and to recharge both batteries (about 10 kW for each battery)

Based on presented figures the values of a rotational speed and a thrust for every flight mode were determined for each examined pitch angles (Tab. 1). For every flight mode, the optimal pitch angle was selected and marked yellow, assuming that the optimal pitch angle would be the one with the maximum thrust over the consumed power ratio for the given rotational speed (so in case of the same consumed power value, the one with the greatest thrust). The values determined in Tab. 1 concern only supply voltage of 360 V, since only small changes in trust and consumed power for some rotational speeds appear with the change of supply voltage (Fig. 5). This attitude leads to determination of the maximum thrust which can be produced by the propulsion from maximum power for each operational mode.
It turns out that the 3-blade propeller would be the most appropriate for assumed operational modes. What is more, the optimal pitch angle is the same and is equal to 15 degrees for every operational mode. This is quite interesting because changes in power delivered to the propeller’s motor differs significantly – the take-off power is 4 times greater than the power delivered during cruise. The ratio of the thrust over the consumed power for these operational modes is within the range of 0,036-0,046. The thrust which corresponds with optimal rotational speed value (1000-1500 RPM) is equal to 100-250 N from each propeller, what is suitable for the required thrust for horizontal flight (about 340 N from both propellers).

Tab. 1. Flight modes with their assumed consumed power and velocity and determined rotational speed, pitch angle and thrust over consumed power ratio, supply voltage: 360 V

Flight mode	Energy source	Consumed power [kW]	Blades [-]	Pitch angle [deg]	Rotational speed [RPM]	Thrust [N]	Thrust/ consumed power [N/W]
Take-off	ICE + batteries	27,5	2	10	ND	ND	ND
				15	ND	ND	ND
				20	2700	880	0.032
				25	2400	800	0.029
			3	10	ND	ND	ND
				15	2750	980	0.036
				20	2400	870	0.032
				25	2100	825	0.03
Climbing with battery cooling	ICE	17,5	2	10	ND	ND	ND
				15	2650	640	0.037
				20	2300	620	0.035
				25	2050	550	0.032
			3	10	2900	650	0.037
				15	2350	670	0.038
				20	2050	620	0.035
				25	1750	570	0.033
Emergency	batteries	10	2	10	2650	390	0.039
				15	2150	410	0.041
				20	1900	390	0.039
				25	1700	370	0.037

			3	10	2300	400	0.04
				15	1900	420	0.042
				20	1700	400	0.04
				25	1450	370	0.037
Cruise with battery charging	ICE	7	2	10	2300	280	0.04
				15	1900	310	0.044
				20	1700	300	0.043
				25	1500	270	0.039
			3	10	2000	290	0.041
				15	1700	325	0.046
				20	1500	300	0.043
				25	1300	270	0.038

5. Conclusions and plans for the future

During the research it turned out, that for chosen propulsion system it is more suitable to control requested RPM than torque, even if the built-in PID controllers enable both operating modes.
As it was described in [8] a few modifications of the ground testbed are envisaged to be implemented. One idea is to replace Linux-based single-board computer with microcontroller-based ECU in order to enhance reliability of the propulsion system. Furthermore, the real battery sets are going to be tested instead of using a power supply only imitating the battery behavior, so as to obtain credible and exact battery charge and discharge measurements. It is necessary to modify the belt gearbox since it is suspected to be the reason of great losses in the generator set. Also cooling system has to be redesigned since original one appeared not suitable for operations with air velocity equal to 0m/s.
In terms of research to be conducted on the testbed there is an idea to perform examinations and compare results obtained in different weather conditions. Additionally, before in-flight tests a wind tunnel tests are expected to measure forces, pressures in requested flow but also to verify drag calculated coefficients of the propulsion components, which are about to be mounted in the PW6 glider. There is also a plan to perform calculations in Fluent software to determine the efficiency of the propeller in order to verify more thoroughly the assumed flight modes.

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7. Copyright Statement

References

[1] https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx
[2] https://ntrs.nasa.gov/api/citations/20100042399/downloads/20100042399.pdf
[3] European Commission. The European Green Deal; EC, European Union: Maastricht, The Netherlands, 2019.

[4] https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf
[5] https://www.clean-aviation.eu/clean-sky-2 (accessed 9 August 2024)
[6] M.K. Bradley, ChK. Droney, „Subsonic Ultra Green Aircraft Research: Phase I Final Report, NASA/CR-2011-216847, Boeing Research & Technology, April 2011.
[7] M.K. Bradley, ChK. Droney, „Subsonic Ultra Green Aircraft Research: Phase II – N+4 Advanced Concept Development", NASA/CR-2012-217556, Boeing Research & Technology, May 2012
[8] https://jet.lilium.com/ (accesed 9 August 2024).
[9] A. Townsend, I.N. Jiya, C.H. Martinson, D. Bessarabov, R. Gouws, „ A comprehensive review of energy sources for unmanned aerial vehicles, their shortfalls and opportunities for improvemnet", Heliyon 6 (2020)
[10] Bright Appiah Adu-Gyamfi, Clara Good, "Electric aviation: A review of concepts and enabling technologies", Transportation Engineering, Volume 9, September 2022, 100134
[11] https://sacd.larc.nasa.gov/asab/asab-projects-2/starc-abl/ (accesed 9 August 2024).
[12] A. Kuśmierek, C. Galiński, W. Stalewski, "Review of the hybrod gas-electric aircraft propulsion systems versus alternative systems", Progress in Aerospace Sciences 141 (2023) 100925.
[13] A. Kuśmierek, C. Galiński, W. Stalewski, "Review of the hybrod gas-electric aircraft propulsion systems versus alternative systems", Progress in Aerospace Sciences 141 (2023) 100925.