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CONCEPT OF A MODERN PASSENGER AIRCRAFT AND ITS MODEL AS AN UNMANNED AERIAL VEHICLE

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ABSTRACT

This article presents the design and development of a modern passenger aircraft modelled as an unmanned aerial vehicle (UAV). Addressing the challenges of climate change and the need for sustainable aviation, the study proposes a hybrid propulsion system combining hydrogen fuel cells and batteries. The conceptual aircraft, featuring a light business configuration with canard wings and a pusher propeller, aims to reduce operating costs and environmental impact. A 1:4 scale dynamic model is used for aerodynamic testing and optimization. The project underscores the importance of geometric, kinematic, and dynamic similarities in wind tunnel experiments to validate the performance of the proposed innovations.

Keywords – Modern passenger aircraft, unmanned aerial vehicle, hybrid propulsion system, hydrogen fuel cells, aerodynamic opitimization, scale model testing

1. INTRODUCTION

The modern aviation industry faces numerous challenges that urgently require solutions due to climate change and current trends. According to the Our World in Data portal, aviation is responsible for approximately 2.5% of global CO2 emissions. The rapidly progressing energy transformation is gradually eliminating fossil fuels and traditional combustion-based propulsion systems, forcing scientists to seek new solutions [Özbek E., Yalin G., Ekici S., Karakoc H, 2020].

For instance, Airbus, as part of its ZEROe program, presents the concept of aircraft powered by liquid hydrogen, which serves as fuel for conventional turbofan and turboprop engines equipped with a modified fuel system, and also acts as a source of electrical energy via fuel cells. The ambitious goal of the program is to achieve zero exhaust emissions in aviation by developing hydrogen propulsion technologies and adapting the infrastructure to support the entire aviation sector's transition to hydrogen power. By 2035, Airbus plans to introduce the first hydrogen-powered aircraft to the market, marking a milestone towards emission-free air transport. Despite hydrogen containing 2.5 times more energy than kerosene, its volumetric energy density is four times lower. This means that the same energy contained in hydrogen, compared to kerosene, occupies more space. This fact prevents the use of tanks in the aircraft's wings. The solution proposed by Airbus is to place tanks in the fuselage, behind the wings, or in the Blended-Wing Body configuration, under the wings.

Meanwhile, Boeing believes that the future of aviation lies in sustainable aviation fuel (SAF), which is produced from inedible plants, municipal, and agricultural waste, reducing CO2 emissions by up to 80%. Currently, these fuels are an additive to conventional aviation fuel due to their high cost. Their significant advantage is that they do not require changes in infrastructure or the construction of existing aircraft engines, making them a ready-to-implement solution.

Another solution aimed at reducing fuel consumption in air transport is the AeroShark technology, developed jointly by Lufthansa Technik and BASF, which mimics the delicate structure of shark skin to reduce aerodynamic drag and improve aircraft fuel efficiency. A special film covered with microscopic ribs about 50 micrometers thick is applied to the aircraft's surface, reducing vortices and turbulence along the aircraft's surface. This leads to more laminar airflow around the aircraft, translating into lower fuel consumption and reduced CO2 emissions. Forecasts suggest that the AeroShark technology can achieve a fuel consumption reduction of about 0.8%, which represents significant savings for airlines and a positive environmental impact. Notably, Lufthansa Cargo pioneered the implementation of this technology on its Boeing 777F cargo aircraft in 2022, and Swiss followed suit, announcing plans in 2023 to equip its Boeing 777-300ER aircraft with AeroShark technology. These actions set new standards in aerodynamic optimization in air transport, paving the way for a more sustainable future.

Reducing carbon dioxide emissions is a problem that everyone takes very seriously. The aviation sector must become more sustainable to develop without negatively impacting the environment. The entire aviation industry is now focused on finding new solutions that ensure more economical and ecological air transport. The priority for designers is now to design aircraft that meet these requirements while maintaining their amenities and visual appeal.

The aim of the project is to design an eco-friendly aircraft that addresses the problem of high operating costs. To achieve this, the following tasks have been set:

- Develop a concept for a modern passenger aircraft
- Design a 1:4 scale dynamic model
- Calculate the propeller parameters using conventional method
- Design a hybrid propulsion system
- Conduct field tests of the dynamic model

2. BASIC PARAMETERS OF THE AIRCRAFT

The presented aircraft is a light business aerial vehicle with canard wings and a pusher propeller configuration, meaning the propeller is located at the rear of the aircraft [Soderman P., Horne W, 1990]. It is designed to compete with aircraft such as the Cessna Citation M2, HondaJet, and Cirrus Vision SF50, which are the most popular aircraft in this class. The approximate parameters of the aircraft are shown in the Table 1.

Table 1 Approximate Parameters of the Conceptual Aircraft

Crew	1 or 2 persons
Passengers	6 persons
Maximum Takeoff Weight	2000 kg
Range	3000 km
Cruise Speed	700 km/h
Power	350 hp
Maximum Altitude	8000 m
Length	10 m
Wingspan	12 m
Propulsion Type	Hybrid propulsion consisting of a battery and fuel cells

Although very light jets (VLJs) have a lesser environmental impact compared to medium jets or big jets, they still emit 15 times more carbon dioxide and 3 times more nitrogen oxides than commercial aircraft. Therefore, there is a significant opportunity to reduce the negative environmental impact in this sector of aviation. Increasing propulsion efficiency by minimizing aerodynamic drag caused by irregular shapes and using eco-friendly hydrogen and electric propulsion systems can make travel by private, small aircraft more environmentally friendly, efficient, and cost-effective. The proposed aircraft, shown in Figure 1, exemplifies how this goal can be achieved.

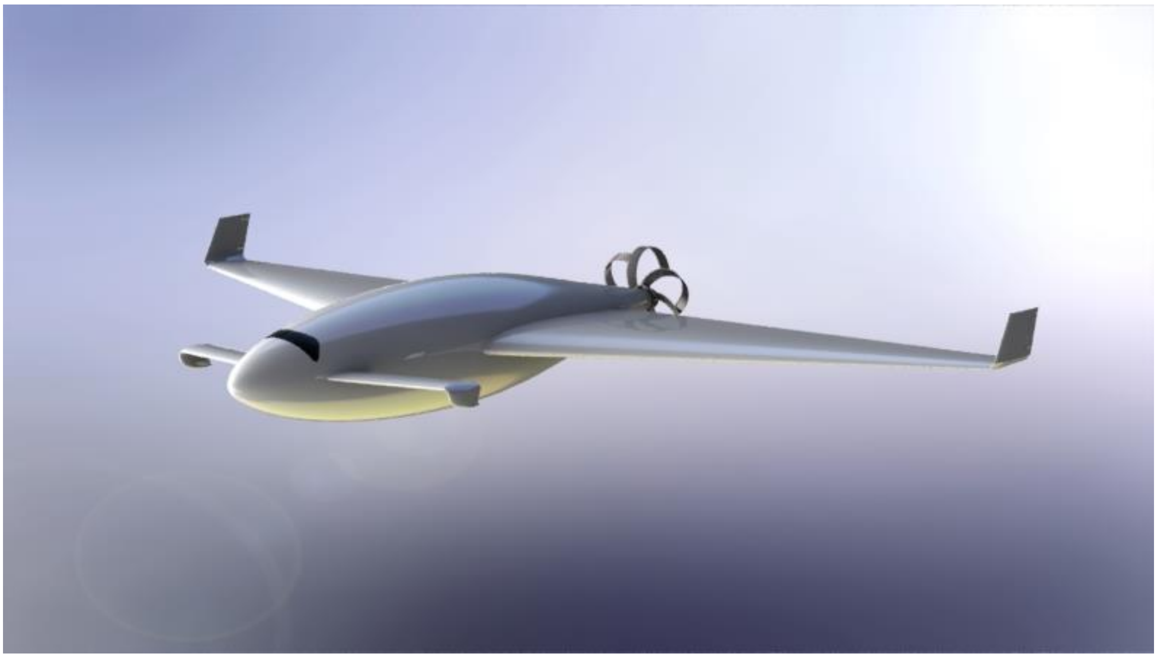

Fig. 1. Visualization of the conceptual aircraft

3. USE OF DYNAMIC MODEL TO STUDY THE AIRCRAFT PARAMETERS

Scale models of aircraft are utilized by nearly every aircraft manufacturer. They allow for testing the aerodynamic properties of a conceptual design without the need to build it in its full-scale form, significantly reducing costs during the design phase. Furthermore, through testing on these models, designers can make improvements at an early stage without the need for field tests of prototypes. The most common use of these models is in wind tunnels. The model is attached to a balance, a device equipped with sensors, typically strain gauges, which measure the forces and moments acting on the model due to airflow. The key parameters measured in wind tunnels are the coefficient of aerodynamic drag and the coefficient of lift force.

To relate the results obtained in a wind tunnel to the real full-scale model, it is necessary to satisfy the conditions of similarity. Two flows are considered similar if, for each corresponding pair of points and at any corresponding time, the ratios of the quantities characterizing these flows remain constant. Three criteria must be met for flows to be considered similar: geometric similarity, kinematic similarity, and dynamic similarity.

Geometric similarity is the most critical condition for similarity [Zohuri, B, 2015]. Without it, achieving the other two conditions is impossible. Geometric similarity requires correct scaling of the dimensions of the real model and precise construction of the model being tested, maintaining all profiles and curvatures as in the real model.

$$\boldsymbol{\frac{L_M}{L_R} = scale} \tag{1}$$

L_M – model dimension [m]

L_R – real dimension [m]

To determine dynamic similarity, the Reynolds number is used—a dimensionless number defined as the ratio of inertial forces to viscous forces present during flow. It is expressed by the formula:

$$\boldsymbol{Re = \frac{l \cdot v \cdot \rho}{\eta}} \qquad (2)$$

l – dimension [m]

v – flow velocity [m/s]

ρ – density [kg/m^3]

η – dynamic viscosity coefficient [Pa×s]

The second important dimensionless number is the Mach number. It is expressed as the ratio of the local velocity to the local speed of sound:

$$\boldsymbol{M = \frac{v}{a}} \qquad (3)$$

v – local velocity [m/s]

a – local speed of sound [m/s]

When Mach number M < 0,3, compressibility effects in the fluid are negligible, meaning that in these cases the dominant criterion becomes the Reynolds number.

Another consideration in the design of a test model is aeroelasticity. The behaviour of an aircraft structure, such as its wing, depends on its stiffness, damping level, and mass properties. Scaling an object to have the same aeroelastic characteristics requires that its characteristics under static load match those of the real model. This means that an aeroelastically similar model deforms in the same way, scaled by the appropriate load. In real aircraft, structural deformations are significant, which poses challenges in selecting materials for constructing test models.

Another type of test involving models is free-flight tests. These tests allow for observing the aircraft dynamics at various angles of attack, including stalls. Changes to improve stability and control can be made quickly and at low cost, positively impacting the optimization process.

In these tests, the Froude number plays a significant role. It is the ratio of inertial forces to gravitational forces and is expressed by the formula:

$$\boldsymbol{F_r = \frac{v^2}{g \cdot L}} \qquad (4)$$

v – velocity [m/s]

g – gravitational acceleration [m/s^2]

L – characteristic dimension [m]

It is particularly important in the study of manoeuvring objects that are geometrically similar. For an aircraft to lift off, it must reach a critical speed that provides sufficient lift force greater than gravity. This critical speed, which is a function of the Froude number, is determined through computational or experimental methods [WOLOWICZ C, BOWMAN, Jr. J., GILBERT W., 1979]

4. HYDROGEN PROPULSION

In today's aviation, engines powered by fossil fuels dominate. Aircraft equipped with piston engines use aviation gasoline (avgas) with varying degrees of lead content. This fuel differs from automotive gasoline due to the addition of tetraethyl lead to increase the octane number. Currently, the most popular variety of aviation gasoline is AVGAS 100LL, which has an octane number of 100, and the abbreviation "LL" stands for "low lead." For turbine engines in civil aviation, jet fuels are used: Jet A-1, Jet A, Jet B, Jet RT, and Jet TS. Aviation fuel for jet engines contains lighter hydrocarbons than diesel fuel for cars. There are separate requirements for aviation fuel and automotive fuel. In Europe, Jet A-1 is used. For this fuel, the crystallization temperature coefficient cannot be higher than -47°C. Jet A was created for the U.S. market with a higher crystallization temperature, and Jet B, with a crystallization temperature of -60°C, is intended for Canada and Alaska.

In recent years, science has increasingly aligned with ecological considerations. Fossil fuels are energy carriers with limited resources and produce harmful substances during combustion. For this reason, automotive companies are increasingly investing in zero-emission drives - electric, hybrid, or hydrogen. Unlike fossil fuels, electric energy is renewable. It can be sourced from wind, sun, or water. Hybrid drives reduce the emission of harmful substances during urban driving by using an electric motor and ensure range on the road with an internal combustion engine. The next step in emission-free transport is hydrogen – an odorless, colorless gas commonly found in nature. When hydrogen is burned with pure oxygen, only water is emitted. When burned with air, water and all other gases that make up the atmosphere (mainly nitrogen) are emitted. This way, we can achieve propulsion without emitting CO, CO2, SOx, or other toxic particles, while maintaining quick vehicle refueling.

The proposed aircraft and its demonstrator model for research will be equipped with a hybrid drive – hydrogen fuel cells plus electric. The electric power will cooperate with the hydrogen power during the aircraft's ascent; once level flight is reached, only hydrogen propulsion will be used. This is due to the more stable operation of the electric source under variable load – hydrogen cells are less stable during load changes and sensitive to flight altitude [Khzouz M., Gkanas E., Girella A., Statheros T., Milanese C, 2019]. A fuel cell is also a lightweight, compact powerplant, which makes it ideal for aerial vehicles [Kim T., Kwon S, 2011]. A simulation of a 2-hour flight at an altitude of 1000 meters with a cruising speed of 120 km/h was also conducted. The schematic of the system components is shown in Figure 2.

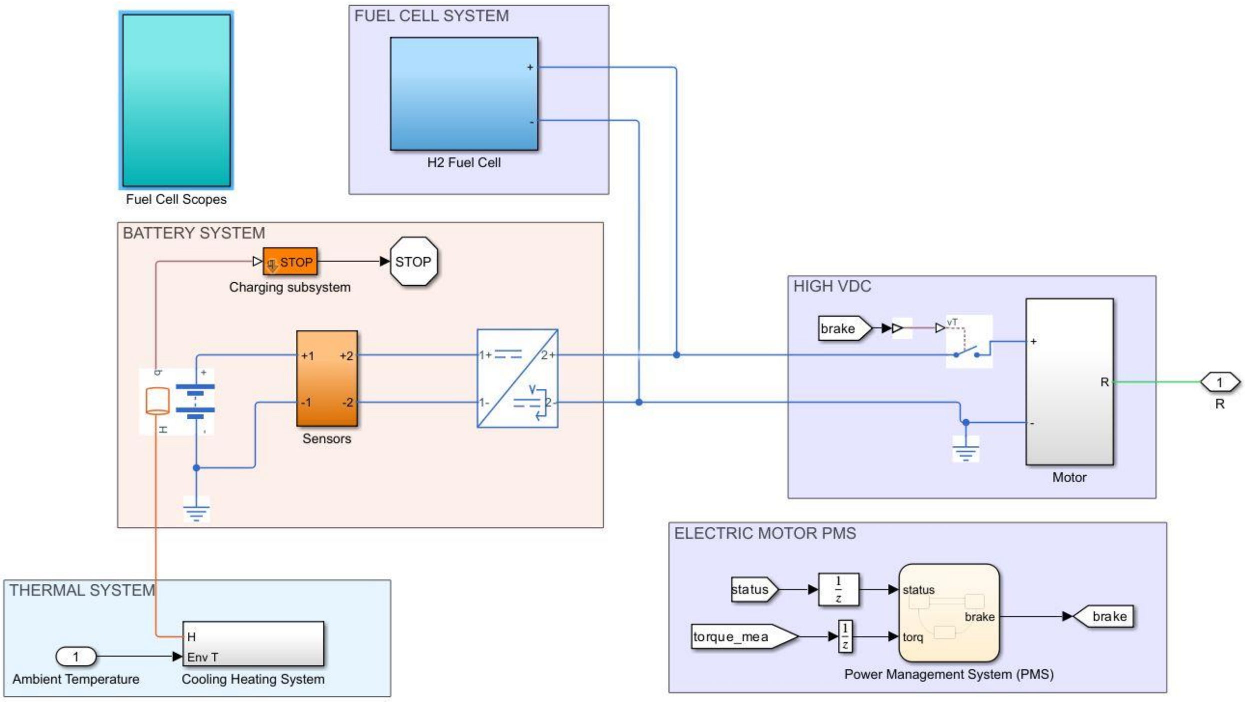

Fig. 2. Diagram of the hybrid propulsion system of the unmanned aerial vehicle

It indicates that for the first half hour, both energy sources operate until cruising altitude is reached. Subsequently, energy is drawn only from the hydrogen cells. For a 120-minute flight, it was calculated that 0.3 kg of liquid hydrogen is needed at an engine power of 2.05 kW. The total energy requirement is 4.1 kWh (including 0.3 kWh from electric batteries). Thanks to this solution, the drone can take off and fly emission-free, maintaining stable power supply. The challenge remains maintaining pressure in the tanks and the availability of hydrogen – it is not a common fuel and still requires development. However, there is no doubt that the future will be based on such twin solutions.

5. UAV PARAMETERS

To achieve the lowest possible fuel consumption, the aircraft fuselage must have the lowest possible aerodynamic drag coefficient [Raymer D, 2012], as this is the main factor influencing fuel consumption. Aerodynamic profiles possess very good aerodynamic properties, which is why they were used to design the fuselage. The chosen profile shape had to maintain a constant height in its middle section to accommodate passengers and had to be symmetrical. The profile selected to create the fuselage is the EPPLER 502, which meets both these conditions. The use of this shape aims to maximize propulsion efficiency by reducing aerodynamic drag and maintaining laminar flow, which is especially important due to the propeller located at the rear of the fuselage. The fuselage shape and the overall appearance of the drone are shown in Figure 3.

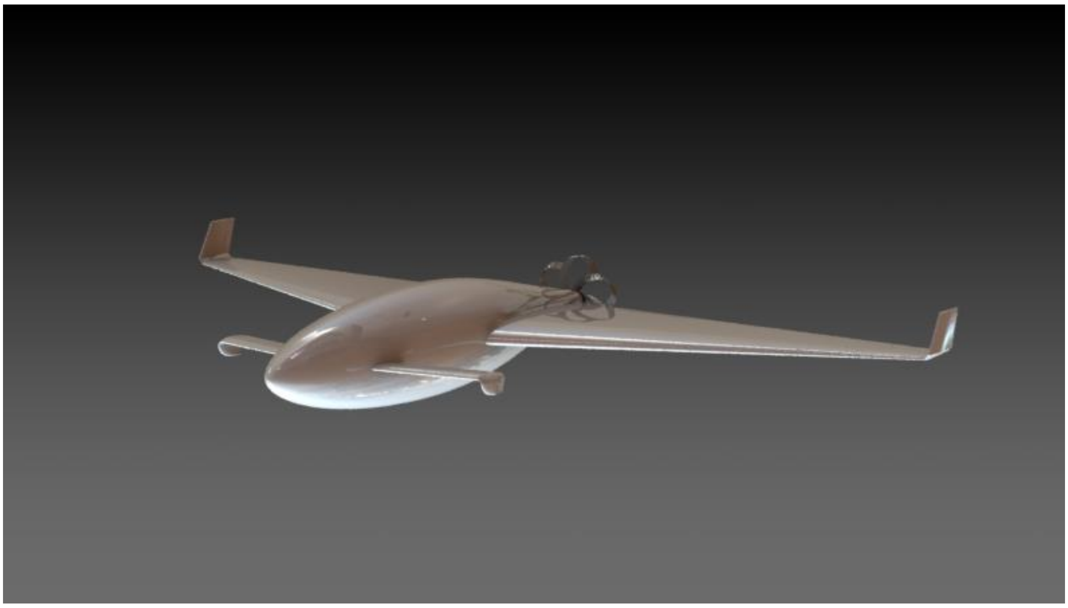

Fig. 3. Visualization of the demonstrator model

The wing configuration of the presented aircraft is a canard, meaning that in addition to the main wing located closer to the rear, there is also a front auxiliary wing. This configuration allows the center of gravity to be moved towards the rear of the aircraft, thus ensuring stable flight. Since the propeller is located behind the fuselage, the hydrogen installation is also located at the back, causing the center of gravity to shift in the direction opposite to the flight path. The wing configuration is shown in Figure 4.

Fig. 4. Main and auxiliary wings of the demonstrator model

The control surfaces include two rudders located on vertical stabilizers at the ends of the main wings, elevators on the front auxiliary wings (which also function as horizontal stabilizers), and ailerons on the trailing edge of the main wings. Future plans include designing wing mechanization elements such as split flaps and slots. The wing geometry is presented in the Table 2.

Table 2 Geometric parameters of the wings

Parameter	Front wing	Rear wing
Chord C_{root} [m]	0,18	1,25
Chord C_{tip} [m]	0,18	0,25
Wing area A_w [m^2]	0,27	2,25
Wing span b [m]	1,5	3
Aspect ratio AR [-]	4	8,33
Taper ratio [-]	1	5
Angle of attack α	1˚	1°

$$\boldsymbol{AR = \frac{b^2}{A_w}} \tag{5}$$

$$\boldsymbol{\lambda = \frac{C_{root}}{C_{tip}}} \tag{6}$$

Due to the size of the main wing, the criterion for selecting the aerodynamic profile was set at a maximum thickness of 12% of its chord length. Based on this, the GOE 693 profile was selected because it met this condition (with a thickness of exactly 12% of the profile length) and because of its lift-to-drag ratio. A sketch of the profile and its lift-to-drag ratio graph are shown in Figures 5 and 6.

Fig. 5. Lift-to-drag ratio charts for the GOE 693 airfoil and RAF 48 airfoil for Re=1000000 (Source: www.airfoiltools.com)

The size of the front wing allowed for the use of a thicker profile, so the RAF 48 profile was chosen, with a maximum thickness of 15% of the total profile length. Due to its simplicity, it is also easier to manufacture from composite materials. A sketch of the profile and its lift-to-drag ratio graph are shown in Figures 7 and 8..

Based on the Cl(α) graphs of the selected airfoils, the lift coefficient derivative of the airfoil was read, which is equal to

$$\boldsymbol{C_{l\infty}^{a} = tan(\varphi)} \tag{7}$$

φ – angle between the function and the horizontal axis [rad]

Then, based on this, the lift coefficient derivative of the wing was determined using the formula

$$\boldsymbol{C_{lw}^{\alpha} = \frac{C_{l\infty}^{\alpha}}{1+k\lambda\cdot\frac{C_{l\infty}^{\alpha}}{AR}}} \tag{8}$$

kλ – coefficient dependent on λ and wing shape [-]

AR – Aspect ratio [-]

The wing lift coefficient for specific angles of attack is determined using the formula

$$\boldsymbol{C_{lw} = C_{lw}^{a}(\alpha - \alpha_0)} \tag{9}$$

α – angle of attack [rad]

α_0 – angle at which the Cl(α) function graph intersects the horizontal axis [rad]

The aircraft drag coefficient is determined by the relation

$$\boldsymbol{C_{da} = 1{,}05\cdot\left(C_{dw} + \frac{\sum C_{di}A_i}{A_w}\right)} \tag{10}$$

$\sum C_{di}A_i$ is the drag of elements not generating lift. In the dynamic model, the only such elements are the vertical stabilizers.

Wing drag is expressed by the formula

$$\boldsymbol{C_{dw} = C_{dwf} + C_{dwi}} \tag{11}$$

Where C_{dwf} is the value read from the Cd(α) graph of the airfoil, and

$$\boldsymbol{C_{dwi} = \frac{C_{lw}^2}{\pi AR}(1 + \Delta)} \tag{12}$$

C_{lw} – wing lift coefficient [-]

AR – Aspect ratio [-]

$$\boldsymbol{\Delta = (0{,}0015 + 0{,}016\left(\frac{1}{\lambda} - 0{,}4\right)^2)(AR - 4{,}5)} \tag{13}$$

Calculations are performed separately for the first and second wings. Then they are summed proportionally to their surface areas.

$$\boldsymbol{C_{lw} = C_{lw_1} \cdot \frac{A_{w1}}{A_{w1}+A_{w2}} + C_{lw_2} \cdot \frac{A_{w2}}{A_{w1}+A_{w2}}} \tag{14}$$

$$\boldsymbol{C_{dw} = C_{dw_1} \cdot \frac{A_{w1}}{A_{w1}+A_{w2}} + C_{dw_2} \cdot \frac{A_{w2}}{A_{w1}+A_{w2}}} \tag{15}$$

Every object enveloped by air produces lift, so every element of the aircraft is a lifting element. However, for simplification of calculations, it is assumed that only the wings generate lift. Therefore

$$\boldsymbol{C_{la} = C_{lw}} \tag{16}$$

The lift force and aerodynamic drag force are determined by the relations [Sadraey M, 2013]

$$\boldsymbol{L = C_{la}\frac{\rho V_\infty}{2}A_w} \tag{17}$$

$$\boldsymbol{D = C_{da}\frac{\rho V_\infty}{2}A_w} \tag{18}$$

ρ – air density [kg/m^3]

V_∞ - flight speed [m/s]

A_w – wing area [m^2]

Since the drag force is known, we can calculate the required propulsion power for flight at a constant speed.

$$\boldsymbol{P = D \cdot V_\infty \cdot \eta} \tag{19}$$

D – drag force [N]

V_∞ - flight speed [m/s]

η – propulsion efficiency [-]

The results of the required power calculations for different altitudes are shown in the graphs in Figures 9-14.

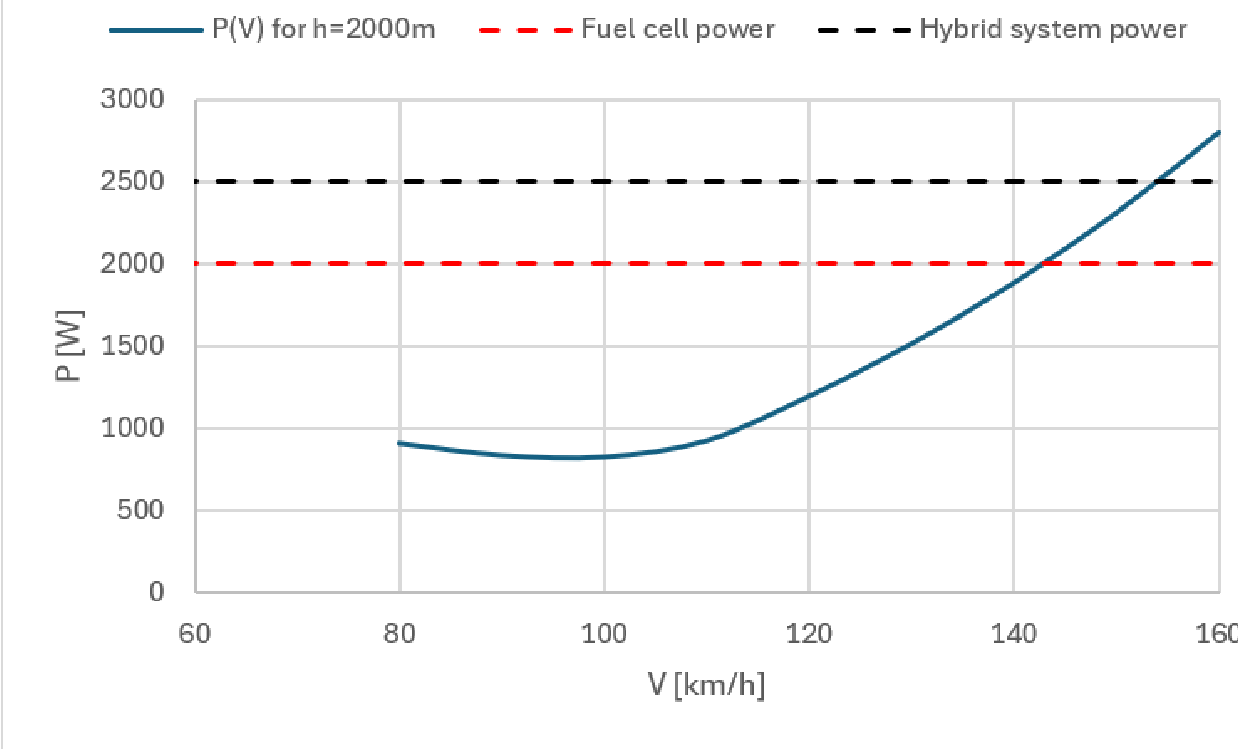

Fig. 6. Graph of Required Propulsion Power vs. Speed at an Altitude of 1000m

As altitude increases, density decreases. According to formulas (17) and (18), density and speed are directly proportional to the lift force and aerodynamic drag. Therefore, at higher altitudes with lower speeds, the generated lift force at the nominal angle of attack of the wings is insufficient, necessitating an increase in the angle of attack, which in turn leads to increased aerodynamic drag. Flying at higher speeds does not require increasing the angle of attack, as the high speed compensates for the decrease in density..

6. APPLICATION OF THE DYNAMIC MODEL

The primary goal of the dynamic model is to analyse its aerodynamic properties, which can be related to the actual concept. Based on these properties, flight stability and manoeuvrability will be evaluated with the current airframe parameters. Field tests and wind tunnel research will allow for accurate estimation of various solutions and their potential modifications. Research conducted on scale models provides the opportunity to measure the properties of the construction without incurring the costs of building full-scale models. This also allows for comparing parameters obtained through calculations with real-world parameters.

Apart from concept studies, the model can also be used for purposes typical of unmanned aerial vehicles (UAVs). One such application is photogrammetric surveying. This involves methods of acquiring data about the Earth's surface and the objects on it using aerial photographs. A drone equipped with a photogrammetric camera takes a series of photographs covering a given area from multiple perspectives. These photos are then processed using computer software to generate a three-dimensional model of the area, which can be used in construction, geodesy, and cartography.

Another application of UAVs is monitoring the Normalized Difference Vegetation Index (NDVI) of crops and forests [Mahajan U., Bundel B, 2016]. A drone equipped with a multispectral camera flies over the studied area, capturing images in two spectral bands: red and near-infrared (NIR). Photogrammetric software calculates the NDVI value for each pixel of the image and generates a map showing the spatial variability of the index in the examined area. NDVI is a valuable tool for assessing the condition of vegetation and its changes over time.

It is relatively easy to calculate and can be successfully used on various spatial scales, from local to regional and global. UAVs adapted for this task are essential tools in modern farming.

7. CONCLUSIONS

For aviation to maintain sustainable development in harmony with the environment, it is necessary to seek and research new propulsion solutions and aircraft designs. Hydrogen is an exceptionally promising technology that has the potential to revolutionize aviation and its environmental impact.

The presented concept of a passenger aircraft, competing with business jets in the VLJ class, is a step towards more sustainable and eco-friendly air transport. The design is adapted for hydrogen propulsion while maintaining aerodynamic shapes, making it possible to use it as a platform for other projects [Bradley T., Moffitt B., Mavris M., Parekh D., 2007].

The demonstrator model will be used to test the concept, adhering to the principles of similarity, as well as for other typical UAV applications. It can also serve as a platform for researching hydrogen technologies and other new technologies related to aviation.

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