

STABILITY ANALYSIS OF A LIGHT UAV WITH SOLAR PROPULSION

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Abstract

Nowadays, stability analysis, including dynamic stability, is a standard element in the design process of new aircraft. Existing tools allow for the assessment of flying qualities at an early stage of the project. This is particularly important when the aircraft being designed is unconventional in any sense, and the designer's intuition and experience can be misleading. This paper presents the results of research on an experimental solar-powered UAV. The untypicalness of this seemingly conventional system is dictated by the type of propulsion. To achieve the best possible projection of solar rays onto the solar cells located on the upper surface of the wing, a special airfoil family was developed and applied providing optimal aerodynamic twist. It is characterized by a flat upper surface over a length of approximately 75% of the chord. Furthermore, the lightweight structure (total mass less than 4 kg – including 0,8kg of photovoltaic cells), its considerable size, and the arrangement of special equipment forced a relatively high center of gravity. Therefore, three features qualify this UAV for particular attention in terms of stability: low surface loading, the location of the center of gravity, and the untypical main wing airfoil. The paper presents the results of tests on various configurations, differing in wing and tail size. The impact of these geometric parameters on mass and inertia characteristics, was considered. The best configuration was selected and tested during the first flights.

Keywords: Dynamic Stability, Solar Propulsion, UAV

1. Introduction

Given the growing volume of air traffic [1], reducing emissions from the aerospace sector is becoming increasingly important. This is advocated in numerous national and international programs and required by national and international institutions [2–6]. This isn't just about reducing CO2 emissions, which are low compared to +other sectors of the economy [7]. Vehicles traveling through the atmosphere also emit significant amounts of water vapor, nitrogen oxides, and other pollutants. They also create condensation trails. The primary problem lies in the altitude where these emissions occur. Most sectors of the economy emit pollutants into the low troposphere, where, for example, CO2 is relatively easily and quickly captured and bound by plants. Aerospace is the only sector of the economy that emit pollutants in the stratosphere and higher, where pollutants remain much longer and are more harmful to the environment [8, 9]. Therefore, it is advisable to take all possible measures to reduce their emissions. The most effective method would be to replace combustion engines with electric motors, which emit no pollutants in the environment where they operate. Unfortunately, this is not an easy task, given the insufficient development of electricity magazines [10]. Therefore, unless revolutionary changes occur, such as powering electric aircraft propulsion systems with microwaves emitted by orbital solar power plants [11], it will be very challenging to introduce fully electric propulsion systems in commercial aviation anytime soon. Therefore, it is worthwhile to utilize electric propulsion whenever feasible, thereby circumventing the energy storage problem. It is also worth considering replacing some traditional aerospace services with other services, implemented in an innovative manner that reduces emissions. Examples of such services include observation and

https://doi.org/10.71945/icas2026_0219

telecommunications, currently provided by satellites launched into orbit using rockets powered by internal combustion engines. These satellites could be replaced by so-called pseudo-satellites, i.e., electrically powered aircraft or airships flying in the atmosphere at high altitudes for many months over a designated area [12, 13]. These pseudo-satellites could harvest energy from the Sun during the day using photovoltaic panels and store it, for example, in lithium batteries, allowing them to continue their propulsive flight at night. The first designs for such pseudo-satellites have already been implemented and appear to confirm the feasibility of building and utilizing these vehicles [14]. This would reduce emissions, as they would emit no pollutants from takeoff to landing. This would also alleviate the problem of depleted satellites remaining in orbit, as well as the issue of the number of active satellites in geostationary orbit. However, designing such pseudo-satellites faces significant technical challenges. One of these is the lack of reliable information on the properties of electric propulsion systems in the higher atmospheric layers. It can, of course, be assumed that a propulsion system that does not involve combustion is insensitive to changes in flight altitude. However, this leads to the questionable conclusion that any electric aircraft can achieve transonic speeds at sufficiently high altitudes. This conclusion stems from the fact that as altitude increases, an aircraft must fly faster to balance its weight despite the decrease in air density. This increase in speed is possible because the reduction in air density has the same effect on both lift and drag. Simultaneously, as altitude above sea level increases, the speed of sound decreases. At a sufficiently high altitude, the aircraft's maximum speed curve would therefore have to intersect with the speed of sound curve, were it not for wave effects such as increased drag and a decrease in propeller efficiency. However, it seems unlikely that a delicate aircraft operating as a pseudo-satellite could accelerate to such high Mach numbers. Most likely, there's some as-yet-unknown cause preventing such acceleration and reaching ever higher altitudes. The project presented in this article aims to uncover the effects that limit the performance of the electric propulsion system, and thus also the aircraft's maximum ceiling and maximum flight speed at high altitudes [15].

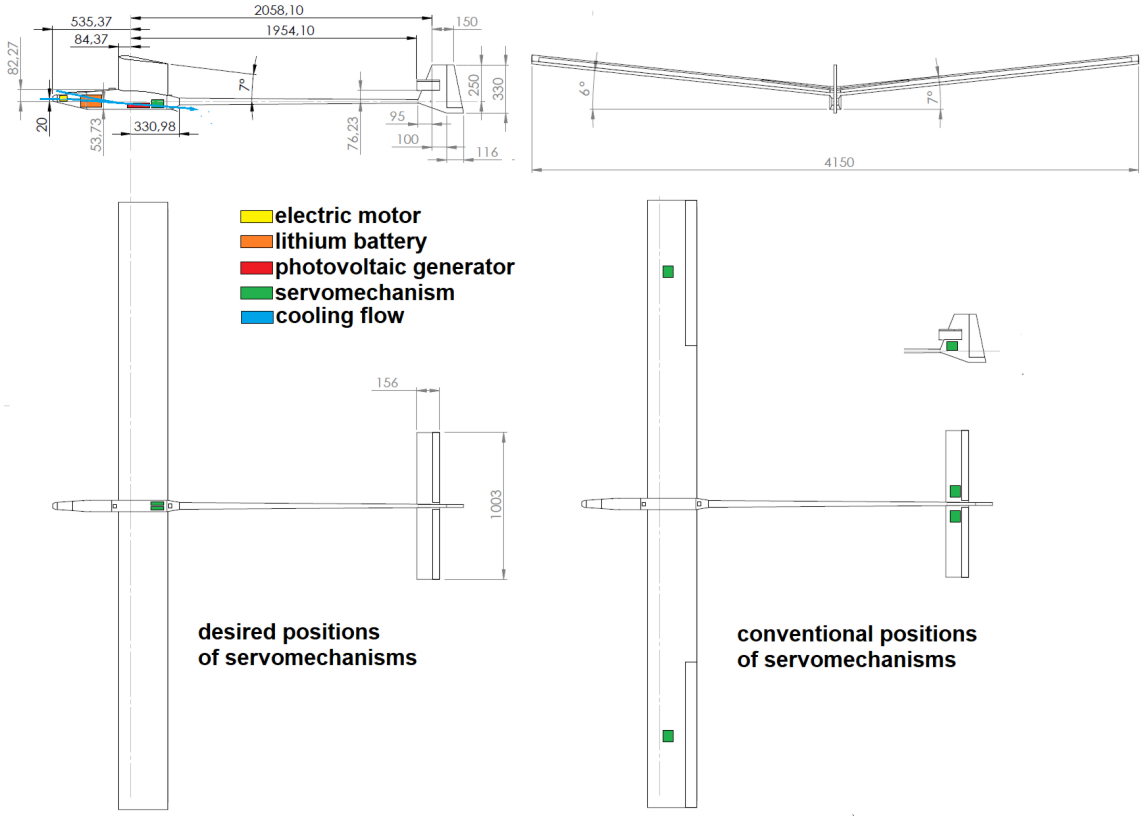


Figure 1 – Research platform, its "hot" components and servomechanisms.

2. Configuration

Since the causes limiting the performance of electric propulsion systems at high altitudes are currently unknown, they cannot be simulated in laboratory conditions - it is unclear what should be simulated. Therefore, the decision was made to build an inexpensive and user-friendly aircraft capable of high-altitude flight, thereby testing the properties of its propulsion system components.

Conducting such an experiment should reveal the phenomena occurring and enable further, more precise research. Among the many aircraft configurations, an airplane was chosen because it seems most similar to a future pseudo-satellite than, for example, an airship. Assuming the propulsion system is powered by photovoltaic panels, the airplane can fly at high altitudes for as long as an airship, while being smaller and less weather-sensitive. It was also assumed that the future pseudo-satellite would also have characteristics similar to a motor glider, i.e., high aerodynamic lift/drag ratio and power factor achieved through high wing aspect ratio, as well as the lowest possible wing surface loading, while maintaining a relatively high power loading on the propulsion system. This also translates into motor glider-like performance, particularly a low climb rate. However, this minimizes the number of necessary photovoltaic panels while ensuring sufficient wing surface area on which they could be installed. However, this concept still poses a problem with the installation of the photovoltaic system, as the long, slender, and lightweight wings will be subject to significant deflection, especially during flight in turbulent atmospheres. This means that the panels will bend during flight, following the bending of the wings. Therefore, they should not be simultaneously bent in a perpendicular direction, i.e., along the wing chord. For this reason, a family of aerodynamic airfoils was developed, characterized by a flat upper surface from 25% of the chord to the trailing edge and varying camber line [16, 17]. It was also decided to arrange these airfoils along the wingspan to minimize the induced drag of a rectangular wing [17]. A test platform was dimensioned based on these assumptions. It turned out that a motor glider with a wingspan of around 4.15 m, an aspect ratio of around 12.2, and a takeoff weight of around 4 kg could be powered by a motor with a maximum power of around 350W and an optimal power of around 200 W. Assuming the use of a variable-pitch propeller, such a motor glider could reach a flight altitude greater than 20,000 m in a single, sunny summer day, provided that no currently unknown difficulties were encountered. It would also provide redundant power from photovoltaic panels in the form of two independent arrays of panels. The power generated by the panels could then power the motor via a buffer of lithium batteries. The capacity of these batteries does not need to be large, as night flights are not required. An emergency landing is sufficient in the event of a failure of both arrays of photovoltaic panels. A motor glider with these characteristics seems to be a fairly conventional design (see Figure 1). However, it has a rather unusual center of mass, as nearly 20% of the takeoff mass—the photovoltaic panels—is located on the upper surface of the wings.

Furthermore, flight in low temperatures at high altitudes poses reliability issues for avionics. The warm air cooling the propulsion system can, of course, be used to heat its components. However, the servomechanisms, which in conventional designs are located close to the aircraft's control surfaces, remain a challenge. The elevator and rudder servos can, of course, be placed in the forward section of the fuselage in a stream of heated air, but the servos driving the ailerons remain a problem. Placing them in the fuselage would require a reliable mechanical drive to move the ailerons. However, this is difficult to implement on a small scale, given the assumed high wing deflection. Therefore, it was decided to investigate whether ailerons were necessary to control such a motor glider. To this end, the wings were equipped with high dihedral. This allows the rudder deflection, which increases the sideslip angle, also to rotate one of the wings forward. Its high dihedral should therefore induce the roll required to execute a turn. As can be seen, the developed research platform concept poses significant challenges in terms of stability and control of the airframe in flight. This article addresses a few of these issues.

3. Aerodynamic and stability analysis

The analysis was performed by use of the software developed at Warsaw University of Technology [18] - PANUKL (low order potential solver) for aerodynamic analysis and SDSA [19] for dynamic analysis. An example of analyses is presented in Figure 2, which presents the screenshots of their

GUIs. The software tools used to these analyses were widely tested, including unconventional configurations [20]. They are coupled also with FEM software [21].

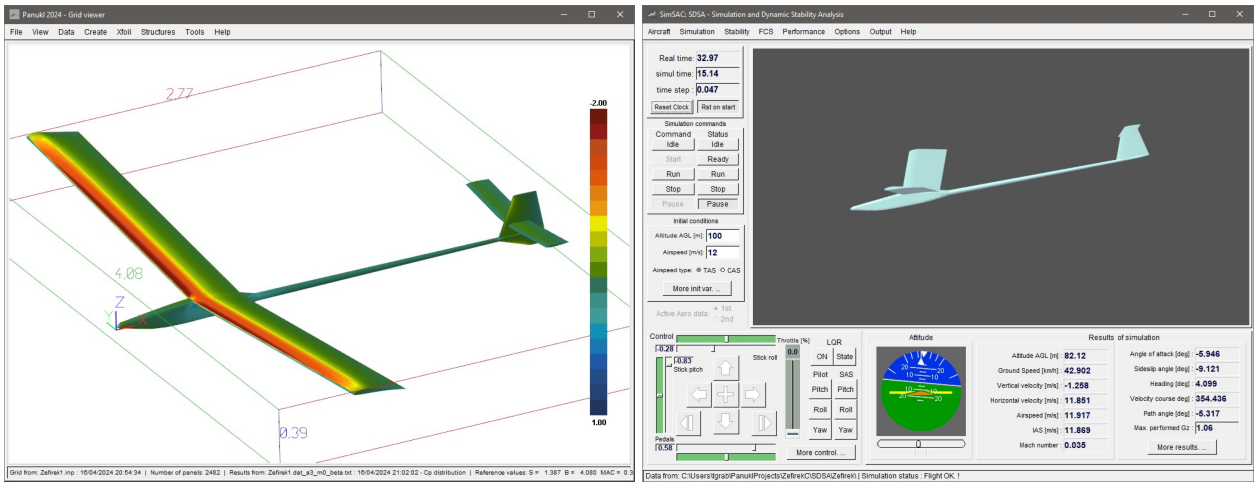


Figure 2 – Pressure distribution case: Alpha=0, Beta=5 (PANUKL software [22]) - left, Simulation test (SDSA [23]) - right

3.1 Initial considerations

Due to the importance of the handling qualities of the designed aircraft, a dynamic stability analysis was conducted just within the early stage of the project. It should be noted that high flight stability during the mission is one of the keys to the project's success. Although the desired version (T tail configuration – Figure 3 – top) demonstrated positive stability margins and met the commonly used criteria to an acceptable degree for standard aircraft, uncertainty related to the post-stall behaviour [24] led to the modification of the tail to a classic configuration with a large vertical stabilizer and a horizontal tail with positive dihedral ((Figure 3 - middle).

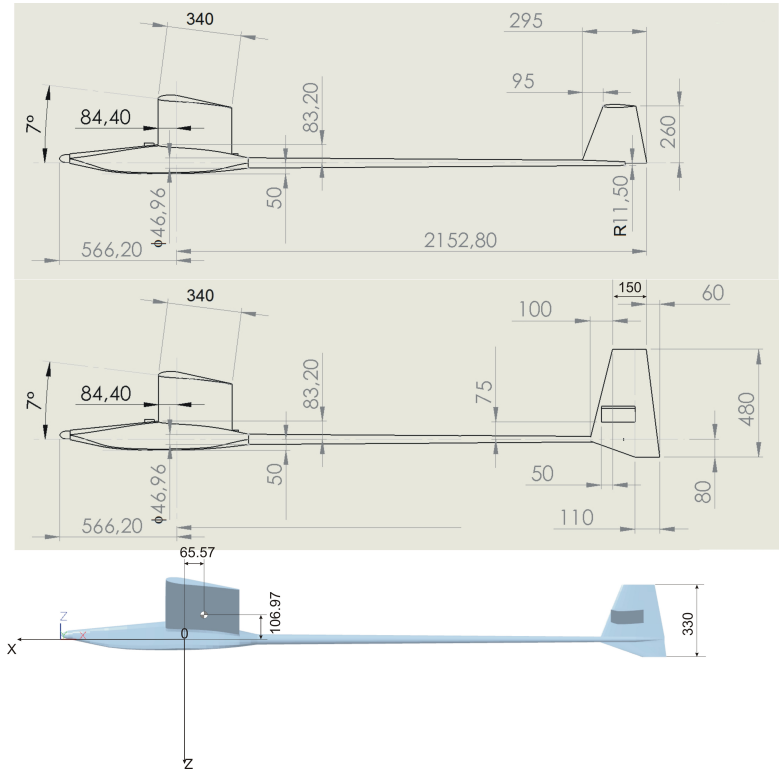


Figure 3 – Evolution of the main layout: preliminary sketches: T tail (top), large vertical tail (middle) and the final configuration (bottom)

The aircraft is designed to fly with economic airspeed so a margin between design and stall angles of attack is small. At the same time it is recommended [24] to place the horizontal tail out of the wake separated from the wing to avoid pitch up and deep stall phenomena. Existing data [24] suggested either very high or very low T-tail. On the other hand these data is not quite appropriate for presented case, so it was decided to apply more conventional tail first and then study T-tail more thoroughly. The second version, although very stable, caused a significant increase in the takeoff weight. Long tail-boom allows to shift center of mass backwards which increases the lift from the horizontal stabilizer but makes an aircraft very sensitive to any excess of mass at the tail. Every additional 10 grams at the tail results with 100 grams of ballast just behind the motor. In the case of presented aircraft this means increase in takeoff weight by about 2.5%. The final version was therefore a slight modification consisting in reducing the height of the vertical tail and thus reducing its area Figure 3 - bottom

3.2 Dynamic stability analysis

The analysis of dynamic characteristics included a classical analysis of typical modes of motion for various configurations, from which the one that best met the adopted assumptions was selected. The results presented below refer to the final version of the aircraft shown in Figure 4.



Figure 4 – UAV Zefirek - after final assembly

3.2.1 Longitudinal modes

First analyzed longitudinal mode was phugoid oscillations characterized by long period and usually good damping. Figure 5 presents results of analysis performed with well-tested software (SDSA [19]), using the linearized and fully nonlinear models.

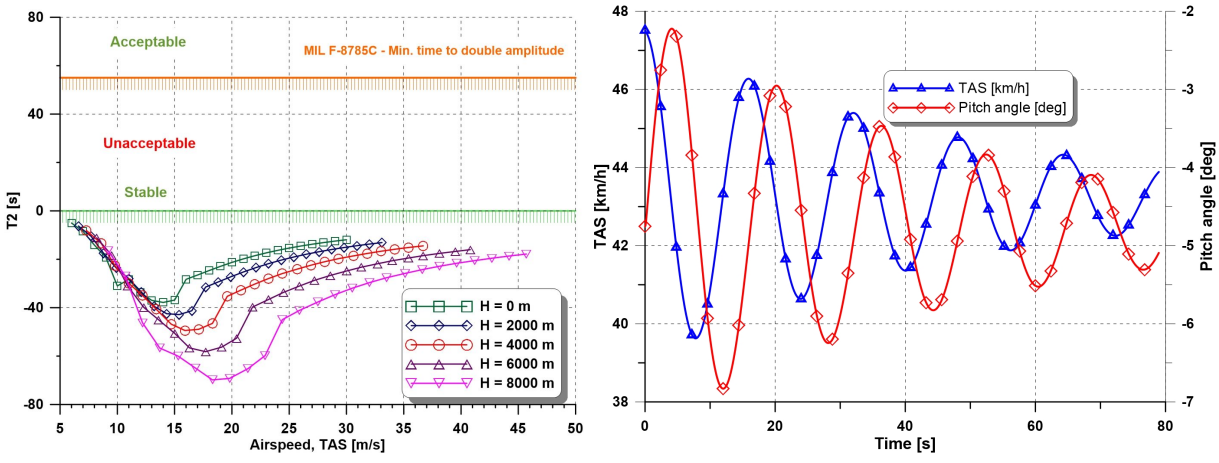


Figure 5 – Phugoid characteristics: Time to half damping (left) and simulation results (time history (H=100m) - right)

The results of both analyses indicate effective damping of the oscillations. Figure 5 left shows the double time (negative values denotes amplitude half time) against the background of criteria defined in MIL-8785C specification [25]. The right graph presents the results of phugoid simulation (time history). The phugoid oscillations were initiated by a disturbance of the initial (equilibrium) airspeed.

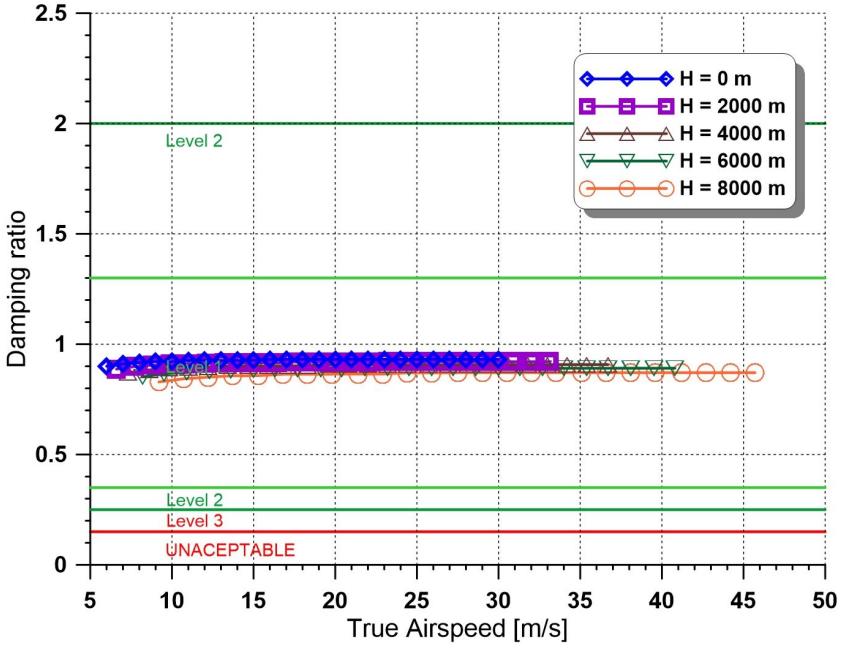


Figure 6 – Short period: damping ratio against background of stability criteria [25]

The second longitudinal oscillation mode is Short Period, for which there are strict requirements in both EASA regulations [26] ("must be strongly damped") and military MIL [25]. The short-period damping coefficient shown in Figure 6 is in the first level of acceptance according to MIL, so the requirements are very well met.

3.2.2 Lateral modes

Lateral modes of aircraft motion typically include one oscillatory mode (Dutch roll) and two aperiodic modes (roll and spiral). While the "roll mode" is naturally strongly damped and does not require special attention in a classical system, the other two modes, especially the Dutch roll, must be subjected to detailed analysis. Figure 7 shows the results of Dutch roll analysis presented against the background of CS-23 criteria (left) and against the background of MIL-8785C citeria (right).

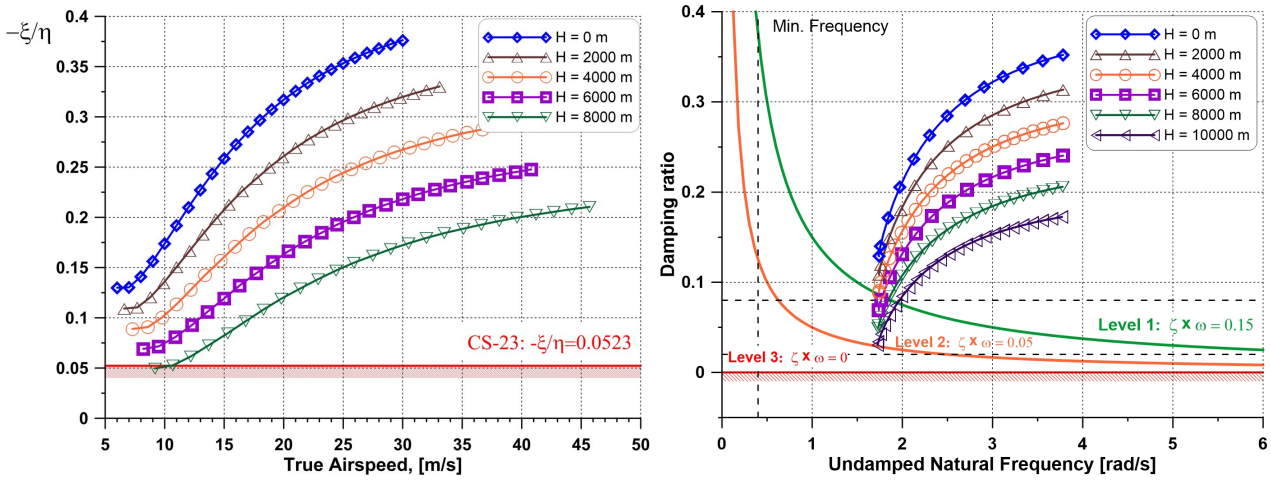


Figure 7 – Dutch roll characteristics against the background of stability criteria: CS-23 [26] (left) MIL F8785C [25] - (right)

In principle, Dutch roll stability is ensured for the full range of flight speeds and altitudes, but at higher altitudes and lower flight speeds the stability measures are at the limit of acceptance for both criteria. Given the high flight altitude expectations for a solar plane, lateral stability issues will require special attention.

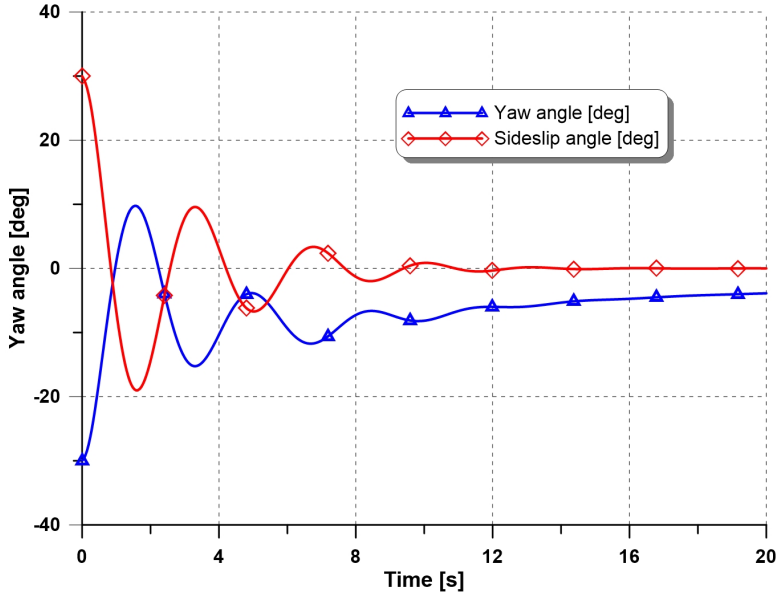


Figure 8 – Dutch roll simulation (H=100m) - time history

Figure 8 shows a nonlinear analysis (simulation) of the Dutch roll, which verifies the eigenvalue-based calculations. The results (time histories of sideslip angle and yaw angle) indicate good damping at low flight altitudes. The Dutch roll oscillations were initiated by a perturbation (non zero value) of the initial sideslip angle.

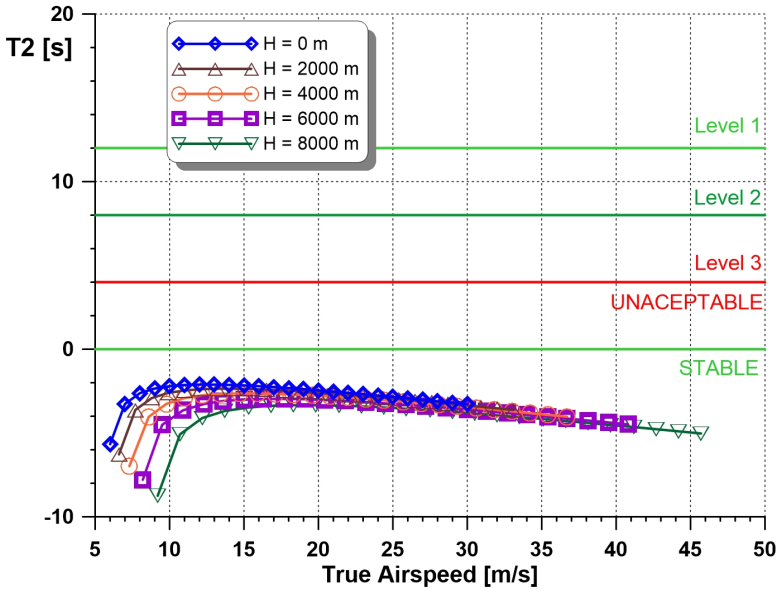


Figure 9 – Spiral: Time to double against background of MIL F8785C stability criteria [25]

The last analyzed mode of motion was a spiral. Typically there are no stringent requirements here, and a slight degree of instability is acceptable. However, given the control constraints and the requirement for precise solar radiation projection, good stability was required in this range as well. Figure 9 shows strong spiral stability, which is the result of the large wing dihedral. This stability level should allow to improve Dutch roll without significantly degrading the spiral characteristics.

4. First flights

The aircraft's first flight was successfully completed (Figure 10). The maneuvers demonstrated the aircraft's general airworthiness and suitability for further flight testing. Its dynamic stability characteristics proved particularly satisfactory. Still, test pilot suggested several modifications. Moreover, a few other modifications may improve the aircraft's performance. Therefore, they are being gradually introduced.



Figure 10 – UAV Zefirek - maiden flight

5. Concluding remarks

It's clear that stability analysis is crucial for aircraft flight safety. However, it is particularly important for those conducting the first flight tests of a new aircraft. In particular, the first flight can end in success or disaster depending on the dynamic properties of the expensive (and sometimes delicate) prototype aircraft, resulting from the decisions made by the designers. Therefore, considerable effort was put into this project to ensure that the first flight and all subsequent flights were conducted safely. A detailed static and dynamic stability analysis was conducted. This led to a number of design decisions that allowed for the successful first flight. The flight itself confirmed the validity of these decisions. However, stability testing of the presented aircraft is still ongoing to improve its performance.

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7. Acknowledgments

This research was funded in whole by National Science Centre, Poland
Grant number: 2021/41/B/ST8/01362.

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