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Design of an Unmanned Return Module for the Conditions of Stratospheric Phenomena Measurements

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Abstract

The aerological observations are one of the key daily routines performed by meteorologists providing the essential meteorological data, such as pressure, temperature, humidity and wind of the upper-air to about 30 kilometres from the surface. The standard procedures are based on the single-use probes that are deployed into the air by a weather balloon which burst at the certain height. Due to drifting during the climbing phase, the balloon is often significantly distant from the initial take-off position. Usually, no effort is made to search for the probe after the meteorological data has been received and after the balloon has burst. In a world where the emphasis is placed on sustainability and reuse of components and equipment, the challenge is to ensure the reuse of these probes and avoid environmental pollution as much as possible. The project of the autonomous stratospheric glider aims to design, construction, and experimental verification of an unmanned aerial vehicle (UAV) performing the function of a return module capable of stratospheric flight. The principle of intended flight is the ability to return to the place of take-off, respectively to a specific destination independently. In cooperation with the Slovak Hydrometeorological Institute, a return module was manufactured and adapted based on the required aerodynamic properties. These include the ability of a stable flight at high speed in the stratosphere as well as having a high penetration, due to strong headwinds occurring in the upper layers of the atmosphere. The glider is deployed analogously to aerological probes using a weather balloon. For this reason, the mission time is relatively long, therefore, the research was also focused on testing the resistance of control components to extremely low temperatures. The result of the research is the manufacture of a fully functional prototype, which was experimentally tested in harsh conditions with an implemented aerological probe that is commonly used in practice. The results of the research show a comparison of computer simulations versus real wind tunnel tests, which have a very similar course and confirm the hypotheses of the research. The outcome of the research is a comprehensively designed unmanned glider, which is capable of flight both in a thin atmosphere and at low altitudes while maintaining the parameters necessary for a safe and rapid return to the place of launch or other destination within the radius of action. In addition, such return module is not suitable only for meteorological measurements but could be used for any measurements. The main advantage is the exclusion of probes finding process after their launch, as they return to their destination. These are primarily applications where the emphasis is placed on the time to find the probe. The presented research is aimed at identifying the applicability of the given solution, its optimization and proposing a practical implementation for users who do not have experience with the unmanned aerial vehicles at a professional level.

1. Introduction

Near space refers to the Earth's atmosphere with altitudes ranging from 20 km to 100 km and is a very complex field that encompasses several subjects of study such as climatology, environmental research, biology and finally physics [1,2]. However, the development and use of near space is currently much smaller than the exploration of the accessible troposphere and earth orbits. General aviation aircraft can hardly fly into near space, and satellites in space are not easy to detect in near space [3]. For this reason, near space is a new research hotspot that is worth more

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observation and detection. The high-altitude balloon is one of the near space exploration devices and has many advantages [4]. First, a high-altitude balloon can achieve very long flight time than a low-cost flight. Compared with other aerial vehicles, the stratospheric balloon has a long endurance, which can achieve sustained and wider coverage for regional observation and detection [5,6,7]. The second example highlights the comparison with satellite, where a balloon at high altitude can carry a heavier payload and increase the accuracy and range of observation, for example, for spatial resolution, and the signal strength of the optical observation payload in near space can be greatly increased [8]. In the third example, payloads in near space with high-altitude balloons can be recycled with low cost and low risk, which is difficult to achieve with satellites.

The research aimed on measuring the aerological condition in the stratosphere faces many challenges, such as the loss of measuring equipment, when the stratospheric balloon reaches the burst altitude, leading to adverse financial losses, as well as pollution due to the frequent use of “single use” probes. The presented paper addresses this problem through the designing, manufacturing, and testing of an unmanned aerial vehicle (UAV) that carries aerological probes and enables their reuse. The proposed model, called a stratospheric glider has been designed with optimal parameters and capabilities in mind for safe return to the launch site (take-off position) with minimal impact on the actual measurements in the stratosphere. Compared to the competition, the glider brings the advantage of high-speed flight and the ability to fly at a high angle of attack (AoA). The main objective of this paper is to present the proposed solution and its advantages over current existing solution for conducting of stratospheric measurements.

In terms of the application of the glider to the measurement and data collection process, one of the main advantages of the proposes stratospheric glider is its ability to transport the measurement equipment to the launch site and to enable its reuse. This approach brings many advantages for measurements conducted in stratosphere. In addition to saving money on the purchase of new probes, it also allows the use of more expensive measurement equipment that would likely be damaged or list in the fall after a balloon burst which is a traditional approach that is commonly used.

From the environmental point of view, the proposed approach also reduces the amount of waste in nature and puts less strain on the environment. This is a major problem that should be addressed by other research teams working with measuring devices that do not return to earth and remain in nature.

Another advantage of the glider is its ability to fly at a high angle of attack. This capability means that the glider can fly a controlled flight even in the higher layers in the stratosphere and measure highly accurately, which other solutions cannot. This feature of the glider opens possibilities for research into stratospheric conditions, not only in meteorology but also in geography and biology. Researchers can use the glider to directly measure chemical parameters in the atmospheric microlayer and atmospheric particulates [9], or to study, for example, the impact of climate change on biodiversity and ecosystems on which more emphasis is being placed than ever before [10].

Not only the glider is able to fly at high angles of attack, but it also had the ability to fly at high speed. Since the glider is launched by a stratospheric (weather) balloon, its ascent trajectory will always be downwind. In the process of returning the glider to the launch site, it will fly in the opposite direction and thus upwind. This poses a challenge due to the high-altitude currents, which can reach the speed up to 400 km/h in extremes. For this reason, the glider must handle an average flight speed twice as high as the average wind speed. This characteristic of the glider also allows to make the measurements more efficient and to acquire more data in less time. This data can be effectively used by researchers to develop and improve climate change models and predictions, as well as to better forecast the weather [11,12].

Overall, the glider also offers several other advantages that are indispensable for stratospheric research. This new approach to measurement in the stratosphere provides many opportunities for education and research and can help in coping with climate change and sustainable development. The proposed stratospheric glider represents a revolutionary idea in the measurement of aerological conditions in the stratosphere. The advantages of this solution lie in its ability to transport the measurement equipment to the launch site and allow reuse, its ability to fly at a high angle of attack, and its ability to fly at high speed. The design of this glider marks a significant step forward for the field of stratospheric measurement and opens the door for further development and research in this area.

2. Materials & Methods

Regarding the methodology, the work was divided into several phases which followed each other chronologically. The first phase focused on defining glider’s dimensional limitations based on requirements of intended application that will be discussed in detail later. After setting of dimensional limitations, we proceeded to evaluation of our requirements using the simulation in computational fluid dynamics (CFD) software environments providing the estimated lift and drag coefficients as well as vortex characteristics of tested prototype configurations. In addition to software simulations, the prototypes were tested in a subsonic wind tunnel to visualize the vortex behaviour during the approximate atmospheric conditions simulated by the tunnel. Both the virtual, and real simulations were conducted at various angles of attack (AOAs). To this point, an important aerodynamic characteristics and limitations are known. Based on this knowledge a suitable shape of wing – delta wing is selected as a wing concept providing the best flight characteristics. In order to generate the lift generated vortex, the LERX technology was chose. The KTH Stockholm -

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L2000 tunnel was used as part of the real-scale testing of the model. It was the results of this measurement that provided verification of the results of computer simulations to confirm hypotheses and flight characteristics.

In the later phases, the research will deal with real flight tests under automatic flight conditions. The information verified in this way will provide a complete picture of the overall properties of the return module before its actual experimental verification in the stratosphere as a result of complex research and prototype design at the TRL7 level.

2.1 Design & Limitations

The goal of design was to create a glider capable of return from high altitudes. To increase the resistance of glider to possible strong wings in high altitudes, small drag is important. To achieve reduction in drag while keeping structural integrity as high as possible a delta wing was chosen as a wing type for our glider. Usage of delta wings brought specific design challenges that had to be overcome. Very first step that was needed in creation of our design was to set limiting dimensions. The following limiting dimensions were chosen:

- Model length: 1.5 m

The defining of dimension limitations was crucial in design process as they directly affected the limitations of wing (glider) design itself. The following limitations were set:

- Wingspan: 1.2 m
- Wing tip thickness: ± 2 cm
- Fuselage diameter: at least 15 cm

The length of the model was set by estimation of root chord needed to create a large enough wing. Regarding the wingspan limitations, the wingspan of 1.2 meter long was set to keep the wings as short as possible to avoid possible flutter problems. The proposed wing tip thickness of ± 2 centimetres was set to allow the spars to fit in without any complications. The minimum diameter of the fuselage was set to at least 15 centimetres to provide a sufficient space inside the glider for the required equipment and isolation material.

Next step was to evaluate the requirements. The real challenge was the wing design as the goal is performing of gliding flight from relatively high altitudes of 30 000 meters. To achieve a long range together with a low drag was vital. Generally, delta wing is a swept wing meaning that drag is reduced in comparison to regular straight wing. This is usually associated with reduction in wave drag, however, preliminary CFD testing conducted shown drag reduction even in case of subsonic speeds. This drag reduction may have been caused by associated reduction in lift. However, is also possible that induced spanwise flow created by wing sweep reduced the velocity loss on leading edge, therefore reducing acting pressure drag. A wing sweep also leads to reduction of lift due to velocity reduction of relative airflow over the wing [13]. Bearing this in mind, a wing sweep had to be as high as possible to reduce drag at low angles of attack whilst keeping enough lift to maintain a level flight. Here it is important to pinpoint that high wing sweep proved keeping high enough lift difficult at higher altitudes where the air density is low. To reach a high gliding range the altitude where the glider begins its gliding descent should be as high as possible, therefore the high lift capability was needed as well. This was of course contradictory to the drag reduction goal, due to fact that high lift usually leads to more drag as well, whether induced drag or parasitic drag due to higher angles of attack [14]. Secondary control surfaces were also not an option due to focus on weight reduction. It was therefore decided to incorporate a vortex lift capability into the design.

Vortex lift is a specific way of generating lift associated mainly with delta wings. The lift generation principle is in this case based on vortex generation over high angle delta wing surface that reenergizes and reattaches boundary layer, this generates low-pressure zones due to high vortex velocity leading to lift generation. To generate vortex lift on delta wing, a thin and highly swept wing flying at high angle of attack is necessary. This would in theory allow a high angle of attack descend at higher altitudes and gradually angle of attack reducing with the increase in air density [15]. However, a high wing sweep needed to generate vortex lift was unsuitable for flight at lower angles of attack where lift could be proven to be insufficient.

Therefore, to create a design capable of vortex lift exploitation, alternative vortex lift generation methods were explored. The first method was a design using forebody strakes, also known as leading edge root extension or LERX for short [16]. LERX-es are extensions of wing leading edge, which are highly swept and thin, fulfilling the criteria for vortex lift to be generated. The vortex created by LERX spreads over the main wing and maintains the wing lift at high angles of attack using the vortex lift generation principles [17]. The design with LERX-es was quite problematic and causes some drawbacks, such as relatively higher weight as the LERX-es had to be 3D printed due to their complicated shape, also they were difficult to attach to fuselage. Therefore, the design itself was redesigned using a double delta concept. Double delta concept was achieved by creating of a wing composed of “two delta wings” of differing wing sweep. A small delta with high wing sweep is in front and seamlessly connects to main delta wing with

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smaller wing sweep. Using this design configuration, it was possible to generate high lift at high angles of attack without use of secondary control surfaces, whilst keeping relatively good characteristics at low angles of attack [18]. To reduce drag furthermore a filet was created at the transition of two deltas creating a seamless curved leading edge that removes spots where air could stagnate.

Sweep angle of the main wing was chosen to be 48 degrees. This allowed creation of a large wing area without use of high sweep angles, whilst keeping constant chord of wing tip. Wing tip chord was chosen to be 30 centimetres long to allow usage of airfoil that provided enough thickness to install spars. This part of wing is responsible for generation of most lift, whether at low or high angles of attack. A medium wing sweep will allow the drag to be reduced while maintaining a decent lift generation capability.

A sweep of forward delta wing is 68 degrees that transitions to sweep of 80 degrees. Transition is created by fillet of 50 centimetre radius. A transition to main wing is created by another fillet of the same radius. A large sweep angle is necessary to allow vortex generation, which is main function of this part of the wing. Additional wing area is a small bonus which will help in lift generation even at low angles of attack. Due to high sweep, the lift generation of this wing at low angles of attack will be small, however drag will be low as well which is desirable.

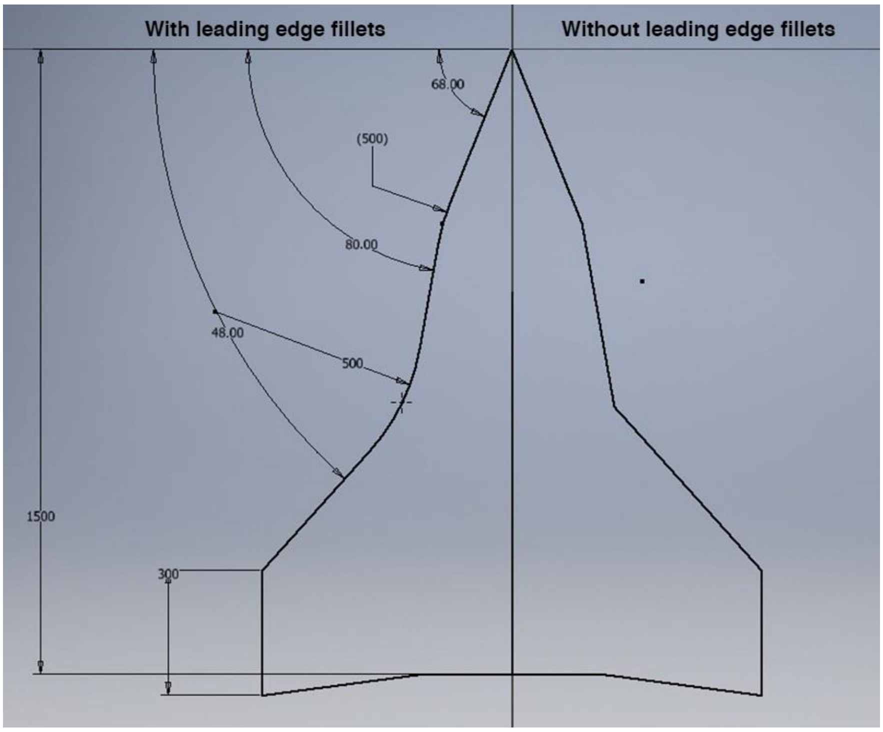

Figure 1 Delta wing dimensions (mm) and sweep angles (left), a comparison of leading edge fillets installation (right)

After the successful wing design phase a fitting fuselage had to be designed. The fuselage had to meet two main conditions, namely:

- Providing of enough space for installation of equipment and isolation
- Design characterized by as low drag as possible

To create enough space inside the fuselage, width of at least 15 cm was required. The cross section of equipment area of fuselage was designed to be 15 cm high and 13 cm wide, which created enough space for installation of equipment and isolation. Cross section of fuselage is kept constant for the length of 21 cm and is in approximate middle. Fuselage is then tapered towards the nose and tail end to improve its drag characteristics. Area created by tapering of fuselage may still be used to install a smaller equipment for which the tapered area of fuselage may still be sufficient.

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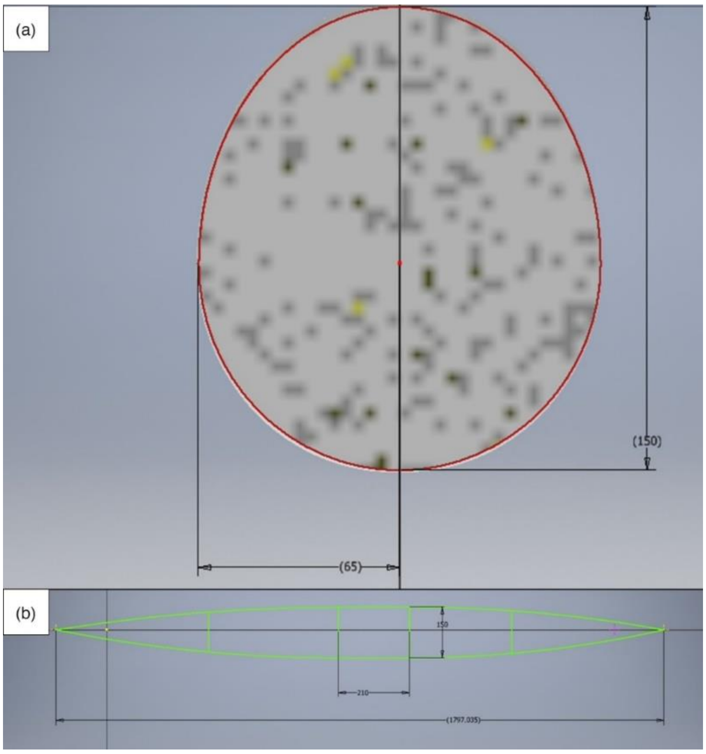

Figure 2 Fuselage equipment area cross-section view (a) and side view (b)

To reduce drag of glider, a tailless design was used. Due to lack of horizontal stabilizer the longitudinal stability will be maintained by use of 4 elevons installed at trailing edges. To improve the stability furthermore, a reflex airfoil NACA 25112 was used to reduce the acting moment that will need to be counteracted by elevons. To help with directional stability a relatively simple vertical stabilizer was installed in the tail end of the fuselage.

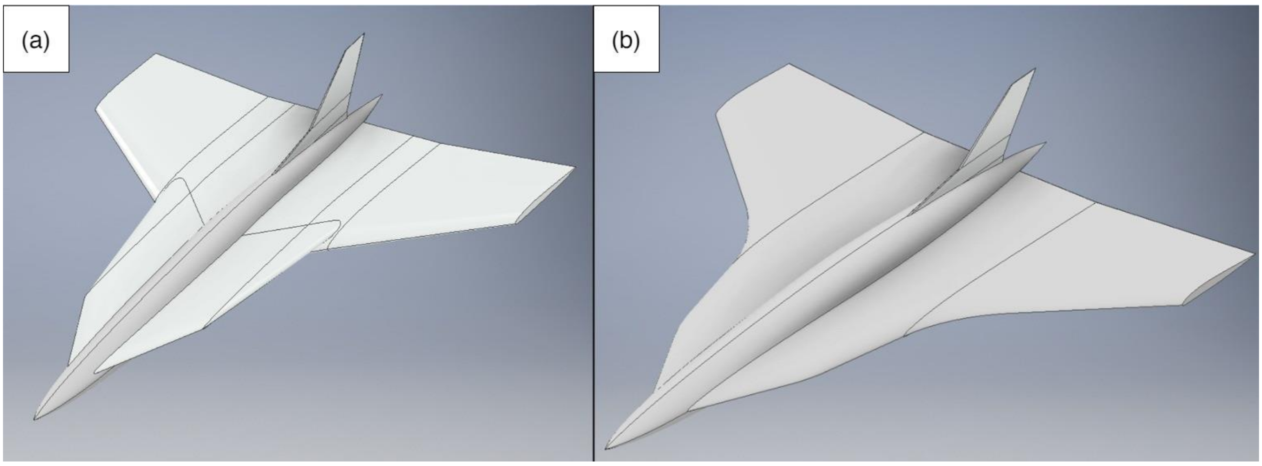

Figure 3: Design with leading edge root extensions (a), design using twin delta design (b)

With design being finalized and drawn it was necessary to conduct testing of the proposed concept. The first testing was conducted in CFD environment, with wind tunnel testing and flight testing to follow.

2.1 Wind Tunnel Tests

The infrastructure of KTH Stockholm, which operates the L2000 subsonic tunnel, was used for testing in the wind tunnel. The model in real scale was constructed from plywood and balsa construction, which was reinforced with aluminum beams. The model was completed with an integrated carrying part for fixing the weight balance. The following figure captures the right-side view of the wing construction of the actual model. the left side of the image

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represents the visualization of the vortex lift that was produced by the LERX system and is essential for the given return module.

Figure 4 A view of the construction of the test model in real scale (left) and a view of the visualization of vortex lift during tests in the L2000 wind tunnel at KTH Stockholm (right)

The measurement methodology in the wind tunnel consisted in the first step in verifying the properties of the model in the test section without real testing and data recording, when instead of a real mass balance, a substitute in the form of a solid body of the substitute balance was used.

Other phases of testing took place with real data collection and the experiments were varied at a maximum speed of 35 m/s and angles of attack from -5° to +35°. During the experiment, it was necessary to pay attention to the limits and capacities of the measuring devices, and therefore the maximum attack angles were adapted to the maximum flow speed. As part of the longitudinal stability and beta angle, angles within plus and minus 15° were tested.

The results of the testing itself are captured in the following chapter.

3. Aerodynamic analysis and results of proposed design

CFD simulations of designed models was conducted in ANSYS Fluent software. Since at time of conducted simulations only a student license was available that limited mesh density, a relatively simple mesh was used that could contain low quality cells affecting results of simulations.

For this fact, a comparison with the results gained for model with LERX-es from wind tunnel testing was conducted. The results showed an average difference of 13.5 % in lift values and 10 % in drag values, with most real lift values being higher than expected based on CFD simulations.

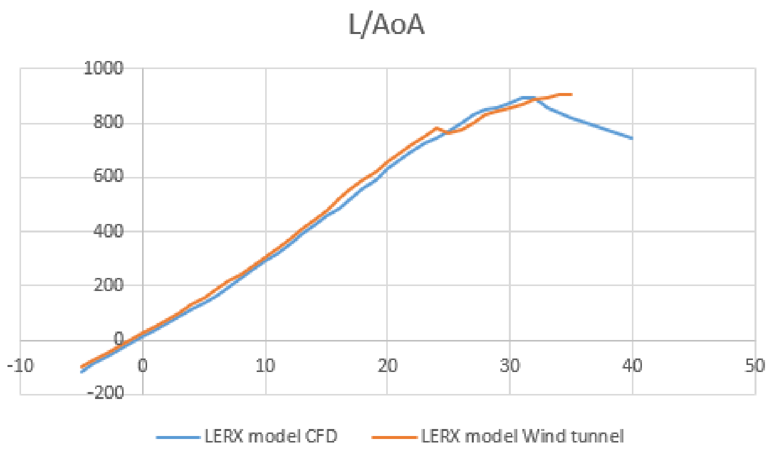

Figure 5 Graphical comparison of Lift values for LERX model

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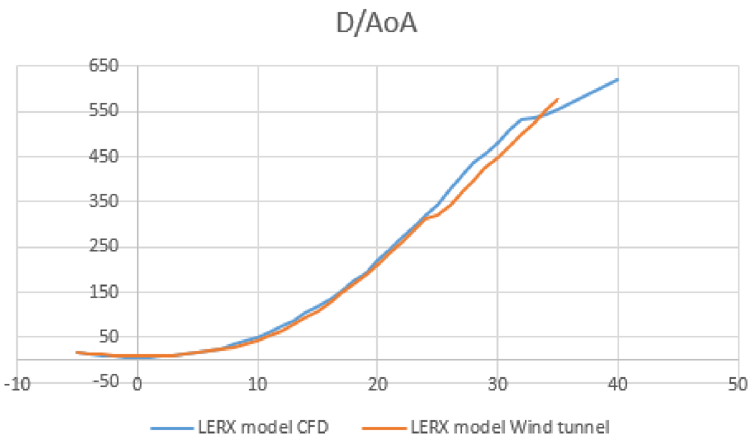

Figure 6 Graphical comparison of drag values for LERX model

Consequently, we can assume that same difference can be applied to simulations of new double delta model and as such assume that real values will be higher than expected. Simulations were conducted for speed of 35 m/s for real gas NIST model at 15°C ISA with realizable k-epsilon, and with scalable wall function viscous model. The results would give us expected lift at sea level, which may not be very interesting for our purposes. However, it is an easy environment to compare results to each other and see how different designs differ from aerodynamic point of view. From results of simulations an approximate force acting on the model that can be used to calculate the aerodynamic coefficients using following formulas (1) and (2) [19]:

$$Cl = \frac{L}{\frac{1}{2} \times \rho \times v^2 \times A} \tag{1}$$

$$Cd = \frac{D}{\frac{1}{2} \times \rho \times v^2 \times A} \tag{2}$$

Where:

- *Cl* is lift coefficient,
- *Cd* is drag coefficient,
- ρ is air density,
- v is relative airflow velocity,
- A is wing area.

With use of these coefficients, we can next approximate an expected lift and drag at any other altitude by changing density in following formulas (3) and (4):

$$L = Cl \times \frac{1}{2} \times \rho \times v^2 \times A \tag{3}$$

$$D = Cd \times \frac{1}{2} \times \rho \times v^2 \times A \tag{4}$$

This only applies with constant Reynolds number value [20]. Therefore, it is necessary to calculate Reynolds number for each change in air density and run a simulation using values used to calculate Reynolds number to check whether the value of aerodynamic coefficients is correct. To calculate value of Reynolds number following formula is used:

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$$Re = \frac{\rho \times v \times d}{\mu} \tag{5}$$

Where:
- *Re* is Reynolds number
- ρ is air density
- *v* is relative airflow velocity
- *d* is characteristic length value

For our calculations a value of mean aerodynamic chord (*MAC*) of main delta wing is used instead of characteristic length valie *d*. *MAC* is calculated using following formula:

$$MAC = rc \times \frac{2}{3} \times [(1 + t + t^2) \div (1 + t)] \tag{6}$$

Where:
- *MAC* is mean aerodynamic chord
- *rc* is root chord
- *t* is taper ratio (defined as tip chord divided by root chord)

Drag and lift forces calculated using above-mentioned formulas, will be used in future estimation of glide path, where angles of descent and descent flight speed will be calculated for each stage of the flight. Due to low air density, the first stage of flight will consist of free fall to gain enough speed to generate enough lift. Using formulas above and results from CFD simulations and wind tunnel testing we can estimate an angle of attack, flight speed and descent angle at which sufficient lift can be achieved. Choosing an angle of attack at which sufficient lift will be generated with as little drag as possible, a relatively constant descent angle could be achieved.

CFD simulations were also used to find the angle of attack at which highest value of aerodynamic efficiency is achieved, this angle being 4° AoA based on CFD simulations and 5° AoA based on wind tunnel testing. A stall angle was estimate based on CFD simulations to be 28° AoA for double delta model. For older model using LERX-es the stall angle was estimated to be 32° based on CFD simulations, however wind tunnel testing showed that wing kept lift up to 35° AoA. Higher angles of attack were unable to be tested due to serious vibrations generated during testing, which may have been result of vortex bursting, but also due to choking of wind tunnel. For this reason, a real stall angle for older model may have been anywhere ranging between 35-40° AoA.

The relation between angle of attack and drag and lift forces is graphically illustrated in and . The shows the difference between LERX and twin delta model, while shows the comparison of all available values. The values for aerodynamic coefficients for CFD results were calculated using equations (1) and (2).

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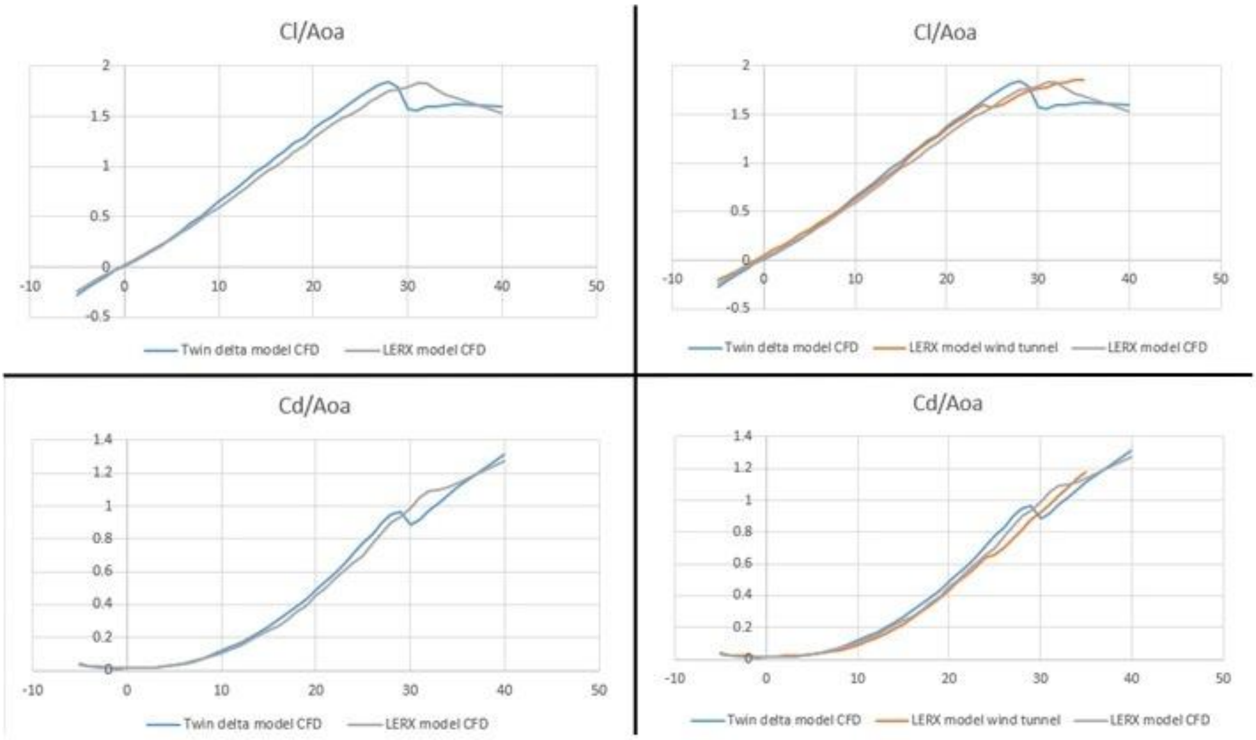

Figure 7 Graphs of aerodynamic coefficients of models (left) and comparing of all aerodynamic coefficients values (right)

Due to use of vortex lift in high angles of attack, a stall angle should be avoided, as at this angle a vortex bursting is guaranteed. Vortex bursting leads to turbulent flow over wing surface possibly affecting the control surfaces which could lead to buffeting that may affect stability and structural integrity by cyclic loading of wing.

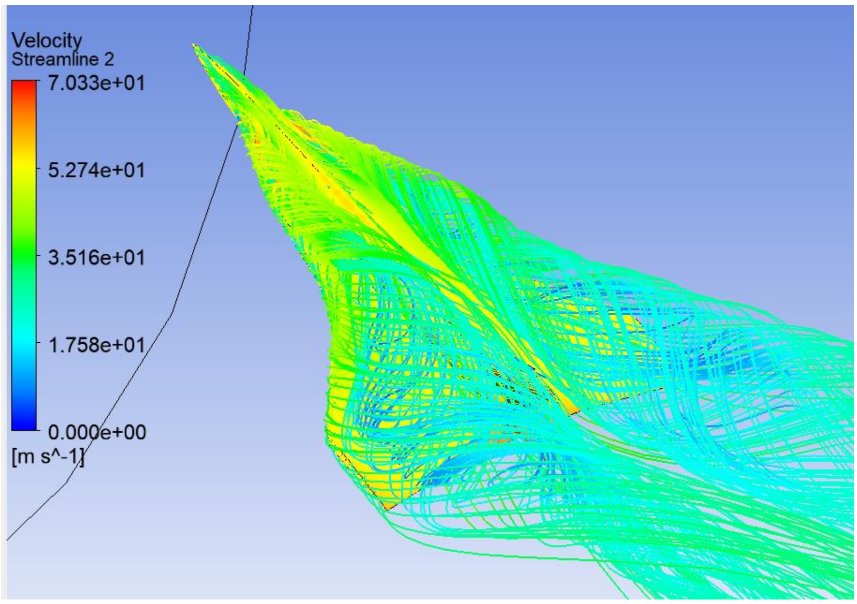

Figure 8 Vortex burst on main wing at AOA 35°

Vortex responsible for vortex lift generation starts forming at around 5° AoA. A fully fledged vortex appears at around 10° AoA. Vortex lift allows our model to maintain lift up to relatively high angles of attack of approximately 28° AoA. Lift generated at these angles of attack is substantial reaching up to 900 N of lift at 28° AoA and at the speed of 35 m/s at sea level, with drag also being substantial. Due to reduced density in higher altitudes, a high drag force experienced at sea level should not be a problem, allowing for exploitation of high AoA lift capability of the model.

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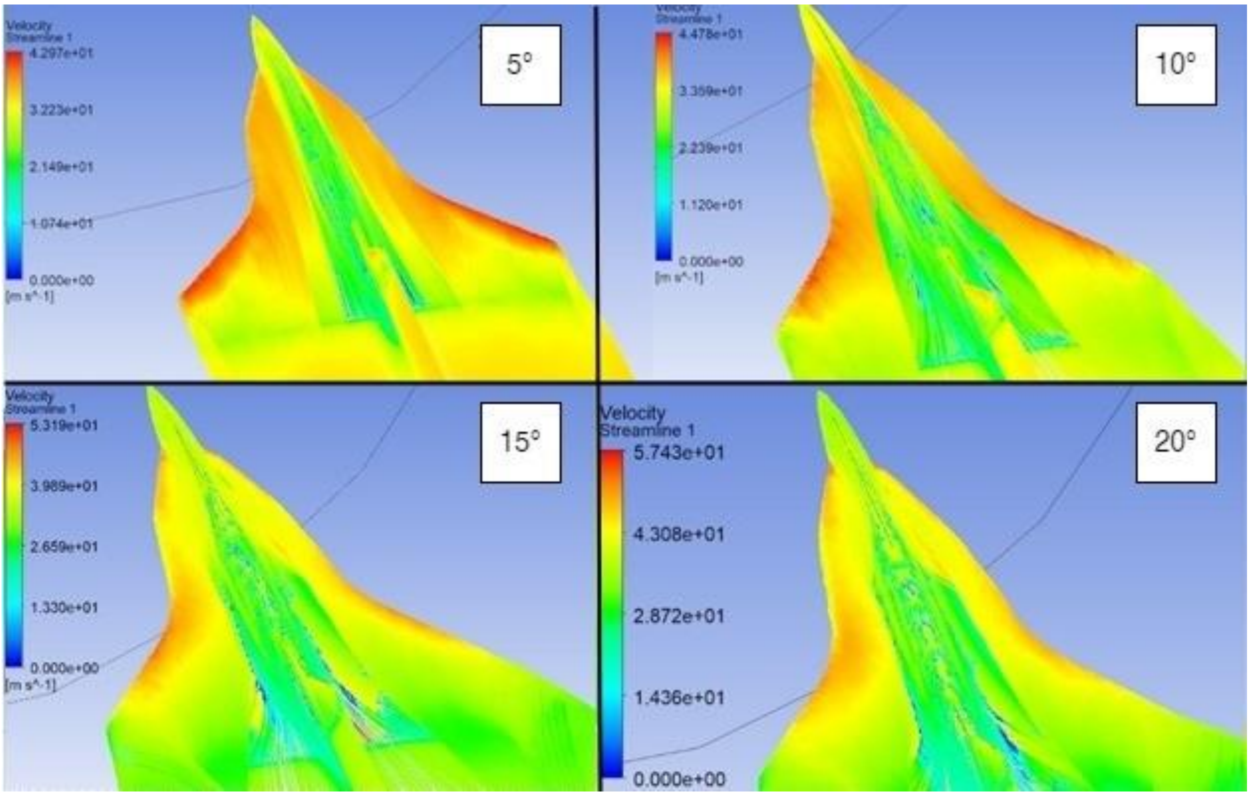

Figure 3 Vortex generation in AoA range of 5-20°

As is shown in , vortex stabilizes at around 15° of AoA and does not change much until AoA of 28° after which a vortex breakdown gradually begins leading to vortex breakdown. Based on the aerodynamic values gained from CFD simulations and wind tunnel testing we can conclude that the angles of attack in the range of 1 – 5° should be used in lower altitudes where high enough air density can be reached, as these AoAs generate sufficient lift with relatively low amount of drag in comparison to higher AoAs. A high lift generated at these angles of attack is not necessary at lower altitudes and would only contribute to additional drag. Angles of attack in range of 10-28° should be used in higher altitudes where low air density makes lift generation difficult. An angle of attack of 4° is recommended considering its aerodynamic efficiency. If the drag at this angle of attack would be too great and consequently impede the flight range, a lower AoA can be selected, providing enough lift generation. A high lift generation allowed by these AoAs will allow the flight even at these altitudes despite the drag being greater than at lower angles. A high drag generated at high AoAs can additionally be used to slow down the model in final phases of the flight.

Conclusion

Research on the stratosphere is currently a still poorly understood part of the Earth's atmosphere and extends to the edge of the Universe, which is even less understood. As technology advances, these places are also becoming more accessible, and in a world of booming unmanned aerial vehicles, there is a use for these applications as well. The present paper addresses the issue regarding sounding aerological measurements and their return to their destination without the need for "single used" technology, or with the risk of loss of technology that must be sought after free fall to the Earth's surface after the experiment is completed and the weather balloon bursts. The research was concerned with the design of an unpowered stratospheric re-entry vehicle - a glider capable of carrying the measurement technology and meeting both the aerodynamic performance and legislative requirements of such a vehicle. Computer simulations were performed within the research with verification of the results in a wind tunnel in a real 1:1 scale model. Based on the results, a model was constructed and subjected to a test flight. As a result of the research, a stratospheric glider has been designed that meets the flight requirements and is capable of flying at both high and low altitudes and is able to carry cargo in the form of measurement technology and aerological probes. Such an unmanned vehicle opens up new opportunities for exploration of the upper atmosphere and allows the use of more complex and costly technology with its safe return to the launch site. As part of a specialized application, such a glider (return module) is suitable for calibrating satellite technology, for example in the Copernicus program [21, 22, 23]. The use of an altitude of approximately 30 km provides an intermediate stage between the calibration of drone aids at low altitudes [24] and between satellites in orbit. From the point of view of metrology, it is an ideal tool that complements

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current calibration methods. In addition to its use in data collection, such a glider is ideal for everyday use in the process of launching aerosondes and reusing them without creating waste in nature, which has a positive impact on the environmental impact of aerosonde measurements.

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