Design of a sailplane based on modern computational methods

Ivo Angelov, Simeon Simeonov
Technical University – Sofia, Bulgaria
E-mail: ivvoangelov@gmail.com simaeronov@gmail.com

Abstract:*The purpose of the current study is to evaluate and apply a new approach to the design process of an aircraft with a high aspect ratio wing, based on modern understandings and development in the fields of aerodynamics and computational fluid dynamics. Conventional methods rely on semi-analytical models for describing different flow characteristics and interactions with bodies. The classical approach requires numerous coefficients to account for unknown effects, what is more, such workarounds are derived for well-defined cases and are not easily applicable for complex problems which could be dangerously misleading. CFD analysis, based on new developments in computational machines, give the possibility of analyzing complex aerodynamic interactions such as shading, downwash, ground effect and vortex shedding. Such use of innovative technology has already proven itself to have beneficial effect on reduction of cost and human error by being able to simplify and speedup many of the calculations without the need of coefficient adjustments.*
Keywords*: SAILPLANE, AEROSPACE ENGINEERING, CFD, FLIGHT DYNAMICS, AIRCRAFT DESIGN.*

1. Introduction

The world of engineering has changed for the better. Nowadays engineers are able to solve complex fluid and structural analysis without drawing a single line on a sheet of paper [1], [2]. Technology has advanced faster than our ability to adapt to use new methods for solving existent problems. The field of design in aeronautics in many cases is an example of industry that falls behind the most modern development methods. The goal of this work is not to prove current methods wrong, but to improve on them the same way Wright brothers improved on the work of previous inventors before them. For the purpose of the research sailplane is designed. The process of developing heavier-than-air machine that is able to stay aloft for prolonged amount of time without the need of an engine is a task that requires approach that differs from the conventional one [3].

Methods in use nowadays rely heavily on semi-analytical equations derived from the experience of previous concepts [4], [5]. The goal of our work is to present and test new way of thinking. The carried process of designing a sailplane is shown in the following paragraphs. Note; the information given is compressed extensively due to paper volume requirements.

2. Defining aircraft mission

One of the most important phases of an aircraft design is the definition of all the requirements that the aircraft will have to meet. Generally those are split into two categories. Ones that depend on the designers' choices such as maximum takeoff weight (MTOW) and ones that depend on legal regulations, such as certification requirements [6]. Skipping a point in the very beginning of the design process will lead to expensive workarounds and costly delays. On (table 1) are shown just some of the requirements that depend both on the designers' choice and legal requirements. It should be noted that filling up this table is iterative processes many of the characteristics of an aircraft depend on each other. Example is the relation between MTOW, Stall speed and Aspect ratio where the stall speed depends on the MTWO and the area of the wing. Data about existing aircraft is also gathered in this phase of the project.

Table 1. *Mission requirements*

No	Factor	Requirement
1	Aircraft Type	Sailplane – Standard class
2	Certification	CS - 22
3	Crew	1 pilor
4	MTOW	300 - 400 kg
5	Stall Speed	17 - 19 m/s
6	Max Speed	50-56 m/s
7	Glide Ration	Above 21
8	Aspect Ratio	Above 12
9	Max Altitude	5000 m
10	Landing Gear	Monowheel
11	Tail Configuration	T – Tail
12	Wing Configuration	High Wing
13	Wing Platform	Tapered

3. Preliminary Design

This is the part of the design process where the team could benefit from existing machines of similar mission. Characteristic features of successful aircraft could be incorporated as a stepping stone in the development of a better design. In the preliminary design more specific layout and sizes of the future aircraft comes to light. Type of control surfaces, means of propulsion, construction materials and more accurate areas for the tail and mail lifting surfaces are only part of all the factors that are considered in phase. In the case of the sailplane that is being designed, the team of engineers has chosen the following characteristics as most adequate for the mission requirements.

3.1 Main Lifting Surface

Top Wing mounting is chosen due to the requirement that the aircraft is intended for field landings. Higher wing means more clearance from the ground and therefore reducing the risk of collision with obstacles. High wing also means more stable aircraft and better characteristics during landing (ground effect is reduced and thus the stopping distance).

Tapered wing planform is preferable due to high aerodynamic efficiency without the need of complex manufacturing process [7]. Aerodynamic and geometrical twist will be present with the goal of increasing efficiency and controllability during stall. 3.2 Tail surfaces

3.2 Tail surfaces

T-tail is considered to be most suitable for the purposes of this project as this configuration provides high aerodynamic efficiency and better clearance of the ground.

3.3 Fuselage

The fuselage does not provide any significant amount of lifting force and its' main purpose is only to carry the crew and provide structural support for the lifting surfaces. This is why the main concern regarding the body of the aircraft is drag reduction.

(Fig. 1) shows the conceptual design on this stage of the design process.

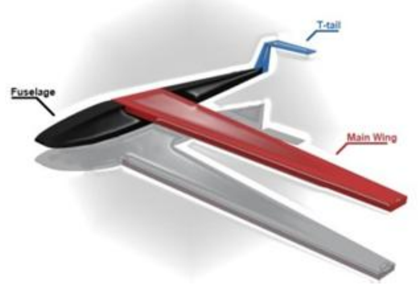

Fig. 1 *Preliminary design*

4. Main Lifting Surface

The actual design of the main lifting surface starts by calibrating the CFD software. For that purpose results are compared with experimental data of a wing tested in a wind tunnel until adequate match is obtained [8]. After evaluation the k-ω SST model is proven to be most accurate. A series of CFD analysis is run in order to find the best matching root and tip airfoil. Tested are combinations of airfoils; NACA43018, NACA43012, NACA633-618, NACA4412, Wort FX-61-163, Wor FX-61-126, GOE533 (at root) and GOE532 (at tip) of which the last two have proven to have greatest efficiency and stall characteristics. Angle of incidence and geometrical twist are also evaluated and corresponding incidence of $+2^{o}$ at the root and -1^{o} tip is found to be beneficial (Fig. 2).

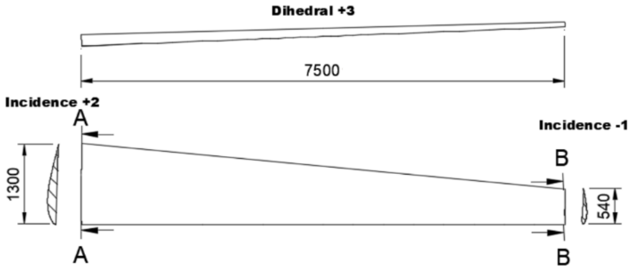

***Fig. 2** Wing characteristics*

5. Fuselage

When designing the fuselage of an aircraft of such type it is important to note the trajectory of the flight. For a sailplane it is specific that the air flow will be hitting the body at an angle coming from beneath the longitudinal axis of the machine. That said the design team has chosen to apply biomimicry and the shapes of several forms found in nature are evaluated in a CFD environment. After careful analysis of the obtained results the final shape of the fuselage is a complex morph between a drop and a whale's body. It is important to note that ergonomics was also taken into consideration as sailplanes are known for long duration missions and safety regarding ground strike (Fig. 3). [9].

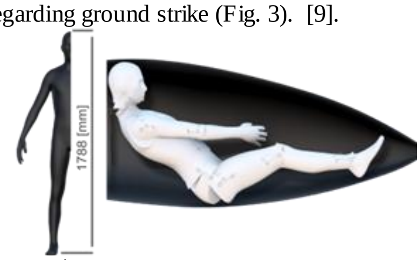

***Fig. 3** Pilot ergonomics*

6. Tail surfaces

The main purpose of the tail surfaces of a fixed-wing aircraft is to balance the moments generated by the main wing and to provide aid with the dynamic and static stability of the aircraft in flight. First step is to analyze separate cases for horizontal and vertical surfaces and then combined model is tested to inspect the aerodynamic interferences (Fig. 4). After selecting the best shape and size for the tail surfaces the whole model of the aircraft is ran through CFD analysis for high angle of attack cases. This is done in order to evaluate deep stall characteristics of the aircraft. It is important to note that all the sizes derived from the CFD analysis up to this moment might be updated due to dependencies down the line of the design process.

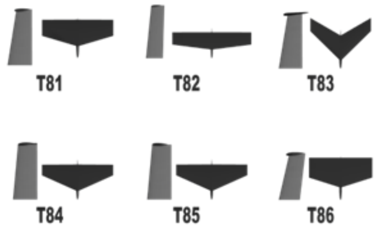

***Fig. 4** Tested Tail Planforms*

7. Static and Dynamic stability of the aircraft

Flight stability is easily considered one of the most important characteristics of an aircraft. Static stability dictates how the machine responds to disturbances and control deviations. The dynamic stability on the other hand is all about how the aircraft returns to its neutral attitude.

7.1 Requirements for evaluating aircraft stability

In order for the static and dynamic stability of the aircraft to be evaluated some additional information is required. Data from the precious CFD analysis is used to estimate all moments acting on the aircraft about its axis. The frame of reference of the aircraft along with the angular velocities and the acting moments is shown in (Fig. 5).

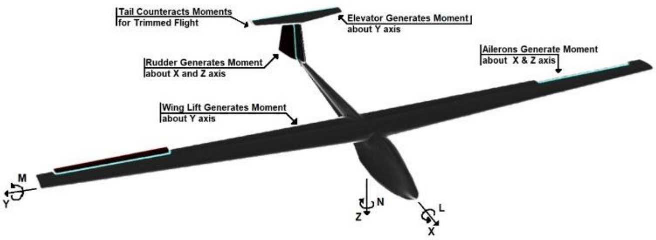

***Fig. 5** Moments acting on the aircraft*

Another very important characteristic of the aircraft is its moment of inertia along the three main axes. In order to obtain this data a full preliminary design of the structure of the aircraft is required (Fig. 6). After finishing this step, new more precise information about the aircraft weight can be obtained. This enables the design team to choose the type and the best location for the landing gear. A fixed monowheel landing gear is selected due to weight requirements.

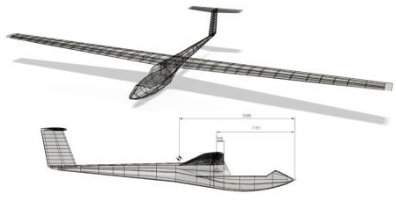

Fig. 6 Aircraft preliminary structure.

7.2 Static stability

Since and aircraft inflight has six degrees of freedom there are three stabilities that need to be established; Longitudinal, lateral and directional. It is important to note that lateral and directional stabilities are related to each other and thus one can be evaluated from the other. Estimation of the static stability is done by running a CFD analysis of the aircraft at various angles of attack and slip. Pitching, Yawing and Rolling moments for every case are studied (Fig. 7).

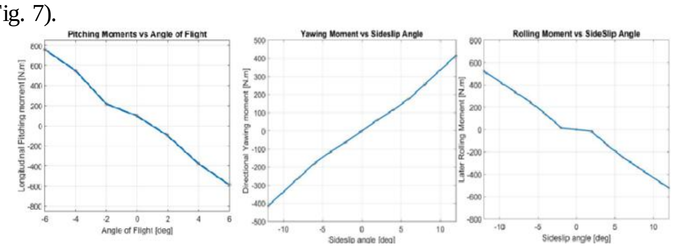

***Fig. 7** Pitching, Yawing and Rolling moment vs angle of deviation*

7.3 Dynamic stability

Evaluation of the dynamic stability of the aircraft is done by running transient simulations in CFD. A dynamic mesh method is used for setting angular velocities of 0.5; 1.0; 1.5; 2 [rad/sec]. After the required data is obtained the equations of motion are solved in Matlab Simulink [10]. Dutch roll and spiral mode cases are analyzed. All results from the study are compatible with the certification requirements (Fig. 8), [6].

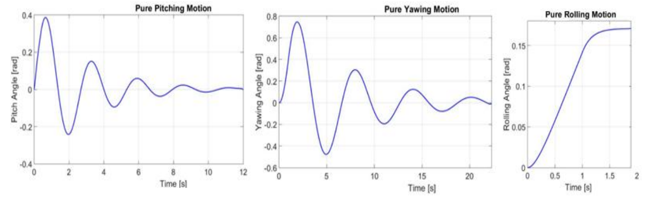

Fig. 8 *Pitching, Yawing and Rolling motion vs time elapsed*

Evaluation of the accuracy is done by comparison with similar existing aircraft such as B-4 [11], LET L-13 Blanik [12] and Schleicher K-8 [13]. (Fig. 10) shows the design of aircraft after the modifications done due to the requirements of static and dynamic stability.

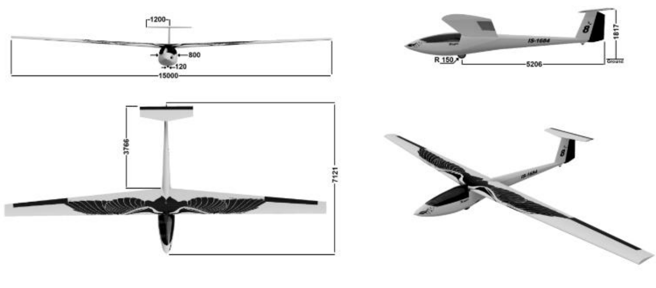

Fig. 10 *Aircraft dimensions after flight stability analysis*

8. Control surfaces sizing

Conventional aircrafts are controlled in the air by means of three moving surfaces; Ailerons (on both sides of the wing) are responsible for roll, Rudder (on the vertical tail) for directional control and Elevator (on the horizontal tail) for pitch motion control. The process of sizing the control surfaces is an iterative process and might lead to major changes to other parts of the aircraft.

8.1 Aileron sizing

It is important to note that a yawing moment is generated due to the drag induced by aileron deflection. In the same manner the rudder generates rolling motion due to its location. Control surfaces are designed by using the requirements for certification of the aircraft [6]. In the case of roll maneuverability it should be possible for the aircraft to achieve a change of direction of 45° for a time equal to the wing span divided by three at a speed equal to 1.3 stall speed. Other requirements include; required maximum force input and stall recovery characteristics. The best location for the ailerons is derived using data from the previous analysis for pressure distribution along the span. (Fig. 11) shows the pressure distribution over the aircraft, used for the sizing of the ailerons. This results are obtained by numerical simulations

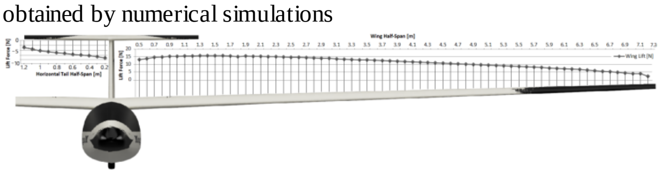

Fig. 11 *Pressure destitution along the wing and tail span*

After choosing the best location for the ailerons next step is to run numerous CFD analysis for different angle of deflection and aileron sized in order to evaluate the characteristics and pick the best configuration (Fig. 12). All results are put into plots for better analysis.

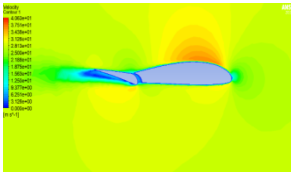

Fig. 12 *CFD of an Aileron*

8.2 Rudder sizing

The rudder of a sailplane is even more important compared to other types of aircraft due to the high aspect ratio of the wing and its use for flying with a sideslip. The rudder needs to be large enough to provide the required force to correct side gusts as well, shown in (Fig. 13).

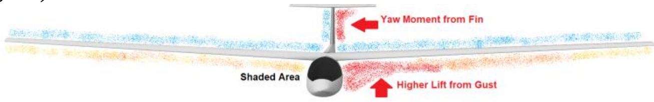

Fig. 13 *Cross wind effects*

The requirements for the rudder are as follows; Aircraft should be able to sustain straight flight during 12 [kn] cross winds coming at 30^{o} to the side at speeds of 1.3 stall speed. Other requirements include that full rudder deflection should not stall the vertical tail and other [6]. After numerically evaluating the aerodynamic parameters of several rudder configurations the following design was chosen (Fig. 14).

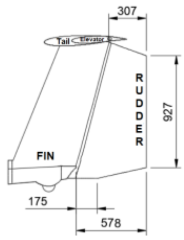

Fig. 14 *Tail Sizing*

8.3 Elevator sizing

The design process for the elevator is carried out the same was as it was for the other two types of control surfaces. The requirements for the elevator are written in the regulations as; For any speed below 1.3 stall speed there should be sufficient elevator input so that the aircraft is able to increase its speed back to 1.3 stall speed. For a tail-dragger configuration the pilot should be able to lift the tail with an angular acceleration of 8-10 [m/s^2] about the main landing gear at speed of 0.5 take off speed. This is required so that the pilot has control over when the aircraft lifts off the ground. Same stall requirements are required here as well. CFD simulations are ran to gather the required data for evaluating the characteristics of the elevator in all expected cases (Fig. 15).

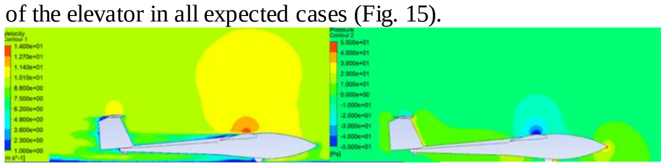

Fig. 15 *Velocity (left) and pressure (right) distribution at takeoff*

9. Cruise flight and trajectory analysis

By analyzing the actual flight characteristics of the aircraft the design team is able to get a better understanding of the quality of their work. The glide ratio is one of the most important factors describing the efficiency of an aircraft. It represents the horizontal distance the aircraft can travel for a unit of vertical distance lost. The differential equations describing the motion of a sailplane are as follows:

$$\left| \begin{aligned} m\ddot{x} &= -\frac{1}{2}C_D\rho S\frac{\dot{x}}{\sqrt{\dot{x}^2+\dot{y}^2}} + \frac{1}{2}C_L\rho S\frac{\dot{y}}{\sqrt{\dot{x}^2+\dot{y}^2}} \\ m\ddot{y} &= G - \frac{1}{2}C_D\rho S\frac{\dot{y}}{\sqrt{\dot{x}^2+\dot{y}^2}} - \frac{1}{2}C_D\rho S\frac{\dot{x}}{\sqrt{\dot{x}^2+\dot{y}^2}} \end{aligned} \right. \qquad (1)$$

The derived equations are solved numerically in Matlab using ode45. As a starting point when solving the equations is taken initial speed of 40[m/s] as this is the speed at which the tug cable is released. All results are put in plots in (Fig. 16).

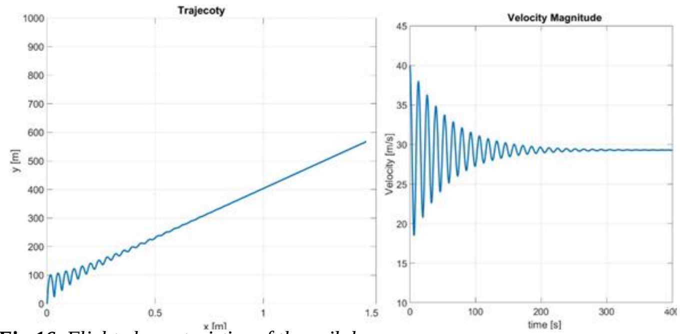

Fig 16. *Flight characteristics of the sailplane*

The calculated glide ratio is 25. The calculated cruise velocity is 29.3 m/s.

9. Conclusion

In the present work, an innovative method based on computational fluid dynamics for determining the aerodynamic characteristics of an aircraft and in particular a non-powered aircraft is proposed. The described method has been successfully applied in the design of a prototype sailplane Magpie (Magpie) IS-1684. The proposed method is proven accurate by means of comparison with other aircraft. Using CFD as a tool for designing aircraft has proven cost and time efficient compared to conventional methods. In the process of our work many 3d computer models have been developed instead of actual models. Based on simulations data from the 3d models is extracted and put in use for evaluation of aircraft characteristics. The steps performed for the overall modeling of the aircraft are described. Numerous numerical simulations have been performed in order to size the wing, tail surfaces, and control surfaces. The static and dynamic stability of the aircraft has been determined. A mathematical model for studying the cruise phase of flight has been developed and applied.

10. References

1. M. Mahdi, *„Prediction of wing downwash using CFD“*, 3rd International Workshop on Numerical Modelling in Aerospace Sciences, (2015)
2. J.Genov, I.Angelov,„Numerical investigation on the effects of the aerodynamic shading between the tower and the blade of wind turbine generator with horizontal axis Numerical investigation on the effects of the aerodynamic shading between the tower and the blade of wind turbine generator with horizontal axis“, IOP Conference Series Materials Science and Engineering, (2020)
3. S. Frati, The Glider, (2007)
4. A.Ortiz, L. Quiroz, R.Köck, *„Aerodynamicperformance analysis of a low-speed acrobatic airplane by numerical simulation“,* Mechanica Computacional, Vol. XXI, p.378 – 391, (2002)
5. D.Coiro, F.Marulo, F.Nicolosi, F.Ricci, *„Numerical wind tunnel and flight tests for P92J and P96 light aircraft“*, 21st ICAS Congress, (1998)
6. European Union Aviation Safety Agency, *„Certification Specifications for Sailplanes and Powered Sailplanes CS-22,*“, (2008)
7. https://www.quora.com/What-is-the-advantage-of-elliptical-wings-over-trapezoidal-wings (04.2021)
8. Bak, C. Fuglsang, P. Johansen, J. Antoniou, I. *„Wind tunnel tests of the NACA 63-415 and a modified NACA 63-415 airfoil“* - Risø National Laboratory, Roskilde, Denmark, (2000)
9. Snorri Gudmundsson, *„General Aviation Aircraft Design Applied Methods and procedures“*, APPENDIX C4: Design of Sailplanes, Basic Mathematical Relations for Glide Performance
10. R. Herman, *„Solving differential equations using Simulink“*, p.20-23, (2017)
11. Pilatus Aircraft LTD. STANS (Switzerland), *„Approved Flight manual and operating manual for sailplane model: Pilatus B4-PC11“*, (1972)
12. Aero Letnany, *„Pilot's notes for the Blanik L-13 Saolplane, 2nd revised edition Czechoslavak Aeronautical Works“* , (1972)
13. Alexander Schleicher GmbH & Co. Ka8 and Ka8 B/C, “Rhonsegler” Operating Instructions. (2010)