UDK: 623.746-519:629.012,621.3.018.1
COSATI: 01-01
doi: 10.5937/str2002009P

Design of the UAV Aerodynamics in Multiple stages

Lazar S. Popović [1)]
Lazar D. Paunović [1)]
Veljko S. Đilas[1)]
Aleksandar M. Milutinović[1)]
Toni D. Ivanov[1)]
Ivan A. Kostić[1)]

This paper presents a methodology for aerodynamic optimization of UAV with VTOL capabilities. Aircrafts such as these usually fly at low speeds and due to that low Reynolds numbers are to be expected. The friction drag is highly dependent on the quality of the production process so unless special measures are undertaken, high friction drag coefficients could drastically influence overall performance of the aircraft. Changes of the geometrical parameters influence not only the induced drag of the wing, but also the distribution of the base drag due to sensitivity to changes of the Reynolds numbers. In order to determine the optimal geometrical parameters of the wing, a code for wing performance analysis was written. All necessary factors were calculated by utilizing the Glauert's solution of the Prandtl's equation for multi-segmented wings. By including experimental data of numerous airfoils optimized for low Reynolds numbers, the base drag distribution, along with the induced drag of the wings were calculated for a wide range of angles-of-attack. The obtained results are presented through diagrams and the methodology for the selection of the highest efficiency wing is described. The design of the T - shaped stabilizer was achieved by utilizing analytical methods while the Vortex Lattice Method, DATCOM and CFD were used for verification purposes.

Key words: **UAV design, VTOL, aerodynamic design.**

Introduction

THE main objective of aerodynamicconstruction and optimization of theaircraftis to ensure maximal aerodynamic efficiency, the ability to successfully complete given tasks and safety. It was in interest of the authors of this paper to design an UAV VTOL aircraft with capabilities to complete a predetermined task.The mission of the aircraft was divided into five stages of flight and analyzed so that the requirements of the observed flight regime could be accounted for in early design stages of the project. The aforementioned stages are vertical take-off, transitional, cruise and maneuvers, transitional period for the purpose of landing, and landing. Transitional period is recognized because this aircraft is in the VTOL category and it is important in the context of aircraft control. Control depends on the quality of the sensors that is utilized by autopilot, calibration factors, propulsion, but also on aerodynamics in terms of geometric and lift characteristics of an aircraftwhich determines stall speed.

Complete mission analysis, in accordance with technical requirements, has been conducted. Several conclusions were made and incorporated into the design methodology. In terms of time spent in a certain stage of flight, in connection with the energy spending reduction, cruising is the most obvious regime for which the aircraft should be optimized. Maneuvers are consisted of turns and looping and should take only a few seconds to accomplish. Aircraft turns were analyzed as a secondary concern, but ability to execute looping successfully had been analyzed in parallel with the cruise. This is done because the looping is depended on the energy achieved prior to the maneuver execution and the level of necessary energy is mostly depended on lift and the geometric characteristics [1]. Since the efficiency of the cruise regime is also depended on the geometric characteristics, among other factors, the optimization of the two regimes are done in parallel.

For the purpose of wing preliminary optimization,a code was written that calculates the base and induced drag distribution and compares them extensively so the wing with highest efficiency that fulfills all requirements could be chosen.The preliminary design of the T-tail surfaces was done by using analytical methods for the quick iteration process and Vortex Lattice Method (VLM) and Datcom for verification purposes.Detailed drag polar calculations of complete aircraft configurationswere done by using an analytical method, Datcom, hybrid approach and CFD for verification purposes.

Concept design

Concept design is fundamental at the beginning of every project. The more thoroughthis phase is, the better the end result is going to be. In this design phase, everything that aircraft has to fulfill, from how much the project is going to cost, how realizable is it, to how to solve particular technical issues has to be determined.

Presented as Paper 028 at the 9th International Scientific Conference on Defensive Technologies, Belgrade, Serbia, 15-16 October 2020
1) Faculty of Mechanical Engineering, Belgrade, SERBIA
Correspondence to: Lazar Popović, e-mail: l.popovic996@gmail.com

Mission requirements

Fig.1 presents a sketch of the flight trajectory that the aircraft must undertake. Before flight, the aircraft has to taxi from assembly position to the area reserved for take-off as an additional requirement,and during flight, the ability to achieve efficient looping and other maneuvers are essential.

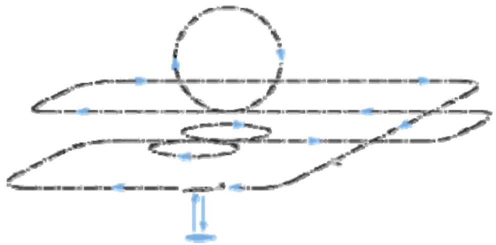

Figure 1. Sketch of flight trajectory

The aircraft has to be able to fly for at least 15 minutes with cruising speed above 60 km/h. The maximal mass of the aircraft is restricted to 25 kg. The basic idea is to design an aircraft that is as efficient as it could possibly be, but also, compact and doesn't need too big take-off and landing area, easy to use, reliable, and can carry payload that can fit into box that has maximal dimensions 1200x250x150 mm. The autopilot has to be implemented so the transitional period could be performed successfully. The landing has to be vertical as well.

Configuration selection process

The design requirements were used to generate possible configurations for the aircraft and its subsystems. These configurations were evaluated using design matrices [2]. The configuration which performed best in each of the design matrices has been chosen. The categories in which concepts were evaluated are plane configuration, propulsion system, tail configuration and landing gear configuration. Accordingly, configurations were compared by rating them based on weighting criteria. This decision process enabled to select the configurations that would optimally fulfill technical requirements.

For the aircraft configuration, features considered for the selection of the best configuration were lift-to-drag ratio, maneuverability, weight, stability, manufacturability and easy payload integration. After a scoring analysis, it was concluded that the selected configuration should aim at achieving the least weight, the best ratio of stability and maneuverability and it should have easiest payload integration. Conventional aircraft configuration with low position of the wing proved to be the most favorable.

The next step in the concept design process was analysis ofpropulsion system configuration with a focus on obtaining low trust-to-weight ratio, efficiency and good hoveringstability while minimizing the size of the aircraft. As mentioned, two factors were of primary importance in this phase: motor efficiency in terms of necessary energy, and aerodynamic efficiency.

After scoring every configuration, it was concluded that retractable engine propulsion systembest fits all of the requirements. The selected configuration is in compliance with design requirements, and has the most balanced relation between aircraft mass, efficiency and ingenuity.

Four candidates were considered for tail configuration: Conventional Tail, H-Tail, T-Tail and V-Tail. The ideal tail would provide sufficient stability for the aircraft while minimizing weight. The T-Tail was selected primarily due to reduction of upwash gradient $d\varepsilon / d\alpha$ which reduces the destabilization effect and allows the horizontal stabilizer to have smaller aerodynamic surface [1].

The final concept incorporates all of the previously discussed components. Fig.2 and 3 displays the aircraft with and without retracted hover propellers.

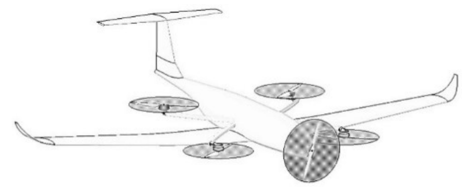

Figure 2. Take-off configuration; engines are outside of the fuselage durig vertical take off and landing

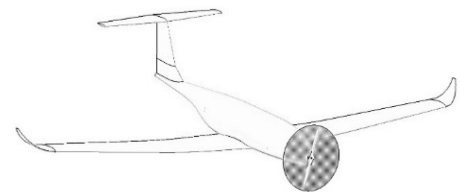

Figure 3. Cruise configuration; engines are inside of the fuselage during cruising

Sizing and initial performance analysis

The standard way to approach the aerodynamic construction of a new aircraft is to analyze existing constructions of a particular type and implement their characteristics in terms of mass, minimal drag coefficient, wing load, horizontal and vertical tail relative volumes [2], wing geometric and effective aspect ratio (AR), lift to drag ratio (L/D) etc. [3] Since this data is mostly available for the General Aviation(GA), some of the key information were not applicable for the successful initial performance analysis. The lift to drag ratio and weight had to be calculated for this particular case. Initial sizing is not only beneficial for determining the performance of an aircraft, but also for the purposes of the project cost analysis. After initial sizing based on recommendations [1], [3] and [4] the global parameters had been established such as approximate lifting surfaces and rough estimation of weight. This had to be done in a few iterations. In the conceptual design phase, it is usual to calculate specific thrust with respect to changes of wing load. In [2] and [3] no guidelines were given for calculating the necessary relative thrust for the looping. The multidisciplinary approach had to be adopted.

By utilizing the guidelines from [1] and [4], with maximal mass calculated in the initial sizing of the aircraft, and by using preliminary methods for drag prediction from [3] and [5] the complete performance of the cruise and looping were calculated for 16 flight conditions. This number of conditions created 16 aircrafts with different geometrical sizes as a consequence, except the fuselage which remained the same for all cases.

With this approach, it was possible to predict the tendencies and gradients of changes in aerodynamic efficiency, the required specific thrust for looping and cruise regimes optimized for different flight conditions (Fig. 5). This data was incorporated (Fig.6) so the wing load and cruising speed were selected in consideration to design requirements.

The preliminary methods of drag prediction [4,5], mentioned earlier, weredigitizedand are using equations (1,2). Equation (3) recommended by [1] was used for calculation of necessary speed for successful execution of the looping.

$$C_{D\min} = \Delta K \sum_{i=1}^{n} \frac{K_i \cdot C_{fi} \cdot S_{WET_i}}{S} + \sum_{j=1}^{k} \left(C_{D\min}\right)_j \frac{S_{ref_j}}{S} \quad (1)$$

$$C_D = C_{D\min} + k \cdot C_L^2 + \frac{C_L^2}{\pi \cdot \lambda \cdot s} \cdot (1+\delta) \quad (2)$$

$$V_0 = \frac{2 \cdot m \cdot g}{\rho \cdot C_{L\max} \cdot S} \cdot \frac{n+1}{n-1} \cdot \sqrt{n} \quad (3)$$

Fig.4 shows the changes in lift to drag ratio for cruise and looping for different sizes of the wing and tail surfaces. The basic idea for this kind of analysis is to see at the very beginning what is reasonable to be expected by the end of the project. It can be seen that the changes are mostly linear, and it can show in what way desired cruise speed can influence lift to drag ratio i.e. aerodynamic efficiency, so the proper steps could be undertaken at the very beginning. Based on Fig.5 it was concluded immediately, in correlation with technical requirements, that the optimal cruise speed should be around 70 km/h. This cruise speed would allow the aircraft to achieve the required speeds with reasonably high efficiency at cruise. It is possible to conclude that to increase lift to drag ratio at cruise, wing aerodynamic surface should be decreased. The upper limit in reduction of aerodynamic surface is the necessary speed for achieving looping which can get unreasonably high at a certain point.

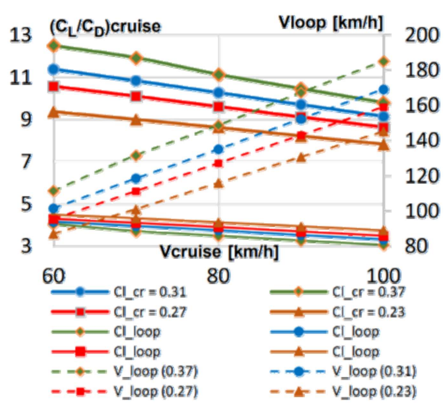

Figure 4. Initial efficiency analysis

Equation (3), based on pilot experience, is overestimating necessary speed about 20% for powered aircrafts, and underestimating speed about 20 - 25 % for gliders for safe execution of looping. The equation uses approximations such as constant load level and thrust equal to drag, which are hard to maintain.

Sizing of tail surfaces was calculated based on theanalysis of wing aerodynamic surface area and tail aerodynamic surface areas relation i.e. S_H/S and S_V/S relations for GA. It was concluded that for distance between the aerodynamic centers of horizontal and vertical stabilizer and aircraft center of mass ofaround $d = 3.0 \div 4.0 \cdot l_{MACW}$, the S_H/S could be up to 0.15, and S_V/S up to 0.1.

Fuselage design is based not only on recommendations [3] for more aerodynamic shape, but also on chosen concept, systems, cables, batteries and all other necessities that have to fit inside the body. It's necessary to have a few iterations to accommodate all required equipment.

Fig.6 shows the implementation of looping specific thrust among other standard performance analysis methods recommended by [3].

Optimal wing loading obtained from the previous analysis (Fig.5) was W/S=8.07. The lift coefficient for cruise regime is calculated to be 0.35. This coefficient is of great importance during preliminary wing design because it represents the optimal lift coefficient $C_{l_{opt}}$ for which chosen airfoil has to have minimal drag coefficient [4].

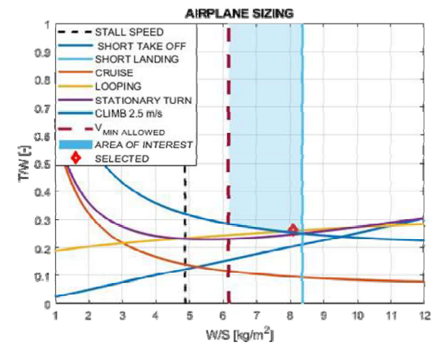

Figure 5. Wing sizing through performance analysis

Preliminary design

The preliminary design was consisted of numerus iterations, so the methods used in this phase had to be reliable, but also quick, so little time and resources are necessary. It is a standard practice to use multiple preliminary methods for verification purposes.

Preliminary wing design

It is a standard practice to decide what airfoils are going to be used beforehand. By using $C_{l_{opt}}$ four airfoils were selected from wide range of experimental results data [6,7,8,9,10], optimized for low Reynolds numbers.

The S9000 airfoil was chosen because of its small drag, high enough maximum liftand low moment coefficients. The data showed that this airfoil is well balanced in comparison to the other analyzed airfoils for various flight regimes.Average Reynolds number for the wing is 590,000.The after selecting an airfoil, its drag polar data for various Reynolds numbers were digitized and implemented as an additional database for later use.

Since the two segmented wings were also considered along with the trapezoid ones, wide range of parameters and restrictions were implemented. For example, the efficiency had to be the highest at the cruise regime in comparison to other wings with different geometric parameters and if the two-segmented wing is analyzed, enough reserve of wing stability had to be provided at the second peek of the lift distribution $\Delta C_L \geq 0.1$ along the relative half span of the wing.

The second step was to analyze the influence of the airfoil drag. The contribution of airfoil drag on very low Reynolds numbers is depended mostly on the existence of a laminar bubble. For example, on 60,000 and 100,000 there is a substantial increase in the drag coefficient. The goal was to have anability to incorporate such divergences into the drag polar calculation of the wing. In cases of UAV design this is not a rare occurrence.While choosing the geometric parameters of the wing with certain aspect ratio and wing taper, there was a change in Reynolds numbers along the wing because of the changes of the local chords. Induced angles $\alpha_i$are aconsequence of the three-dimensional flow around the surface of the wing. The larger the induced angle on a local wing cross section the larger local induced drag, which also reduces the geometrical angle-of-attack(AoA) [2]. That's why it was important to analyze the lift distribution, but this time, theairfoil drag and induced drag distribution as well.Third step was summarizing drag components for every considered wing geometry and then comparing them in easy to understand way so the quick selection of top candidates could be done.

The written program calculates the lift and induced drag distribution by utilizing Glauert's solution of the Prandtl's equation [4] optimized for multi-segmented wings by using equations (4,5,6,7,8,9). The program was optimized for wide range analysis of wing aerodynamic characteristics.By solving the system of linear equations (4), the A_n factors could be calculated. After that was done, the rest of the calculations were done directly. Factor δ represents correction of the induced drag of the wing due to the deviation of its geometry from the elliptical shape. The wing induced drag was then calculated by using (10).

After these calculations, by using wing lift distribution and airfoil drag polar data,as well as the available experimental data for the selected airfoil the distribution of the wing components of the dragwere calculated. The procedure was to use airfoil drag coefficient for the AoA that corresponds with the coefficient of the liftat observed wing cross section airfoil (11) as recommended by [11].

The total drag coefficient (12) of the wing is sum of the two [11,12]. The friction coefficient has a big role in the aerodynamic characteristics of the airfoil, and therefore of the wing [13]. This means that experimental data used for these calculations have to be representative of the production processes that are going to be used for manufacturing of the designed aircraft. In [13] airfoils with standard roughness have substantially larger drag coefficients, on which are based all factors for standard preliminary calculations [4,5]. This means that by using this program and experimental data [13] for rectangular wings, there should be excellent match between the analytical method and the program results. Since analytical methods use approximation of the drag polar, the method of this program should be more detailed and provide more accurate data. The process of results verification is very important one.

For verification purposes of the lift and induced drag distribution, two additional software were used. Fortran code [4] is used for result verification of trapezoid wings, and Vortex Lattice Method as an additional method [14] for trapezoid and multi-segmented wings. They showexcellent match of results of lift distribution and some mismatch of induced drag distribution between the two methods i.e. Glauert's method and Vortex Lattice Method (VLM) near the end of the relative half-span of the wing. This is because VLM [14] calculates induced drag in such a way that δ< 0. This is in conventional theory for clean wings impossible, but it simply represents the differences of the two methods. Because of the scope of this paper, the data could not be shown.

To verify the functionality of the written software and its end results from equation (12), the previously mentioned method was applied. The analytical calculation [5] through use of equations (13,14) was compared to the written program results for multiple rectangular wings. These wings are explicitly used because of the limited data for standard roughness [16]. Equation (14) is simplified form of (2), where $k = 0.38$ represents factor of the parasite drag component [5] in respect to changes of AoA. Fig.7 represent result comparison.Reynolds number is 6.000.000 for every chord on the wingspan.

$$\alpha_a = \alpha_{0S} \cdot l_s \cdot \sum_{n=1}^{\infty} \frac{A_n \cdot \sin n\theta}{\alpha_{0n} \cdot l_n} + \frac{\alpha_{0S} \cdot l_S}{4 \cdot b} \cdot \sum_{n=1}^{\infty} n \cdot A_n \cdot \frac{\sin n\theta}{\sin\theta} \quad (4)$$

$$C_L = \alpha_{0S} \cdot l_S \bullet \sum_{n=1}^{\infty} \frac{A_n \cdot \sin n\theta}{l_n} \quad (5)$$

$$C_{Di} = \alpha_{0s} \cdot l_s \cdot \left(\sum_{n=1}^{-} \frac{A_n \cdot \sin n\theta}{l_n} \right) \cdot \left(\sum_{k=1}^{-} k \cdot A_k \cdot \frac{\sin k\theta}{\sin\theta} \right) \quad (6)$$

$$C_L = \frac{\alpha_{0S} \cdot l_S \cdot \pi \cdot b}{4 \cdot S} \cdot A_1 \quad (7)$$

$$C_{Di} = \frac{(\alpha_{0S} \cdot l_S)^2 \cdot \pi}{16 \cdot S} \cdot \sum_{n=1}^{\infty} n \cdot A_n^2 \quad (8)$$

$$\delta = \sum_{n=1}^{\infty} n \cdot \frac{A_n^2}{A_1^2} \quad (9)$$

$$C_{Di} = \frac{C_L^2}{\pi \cdot \lambda} \cdot (1 + \delta) \quad (10)$$

$$c_{D0}(2Y/b) = c_{D0}(c_L(2Y/b)) \quad (11)$$

$$c_D = c_{D0} + c_{Di} \quad (12)$$

$$u = \frac{1}{1 + \delta} \quad (13)$$

$$C_{DW} = 2.04 \cdot K_W \cdot C_{fW} + k \cdot C_{LW}^2 + \frac{C_{LW}^2}{\pi \cdot \lambda \cdot u} \quad (14)$$

It is possible to see that excellent match between the two methods was achieved. On Fig.6 (right) it is possible to see the break of the calculations. This is because there is no experimental data for greater lift coefficients available. This shows how important it is to have quality experimental data. It would be preferable to have airfoils created by materials with production processes expected to be seen on the designed aircraft.

Authors in [6-10] have tested numerus airfoils that are manufactured with great precisionand withfine surface treatment which gave excellent airfoil performance. But, by analyzing theproduction capabilities, correction had to be implemented to equation (12). Equation (15) represents modification of (12). It is simple, but it was found to be sufficient for analysis of cruise regime and small AoA of the wing.

Fig.7 show the changes in δ due to changes of geometrical parameters of the wing. Wing that has the lowest correction factor δ isn't necessarily the wing with highest efficiency due to existence of a laminar bubble. This method of analysis is not expected to give correct results for taper ratio λ < 0.2. Another restriction of this method is the limited area of analysis with wing sweep angles greater than 10°.

The first iteration was the wide range analysis of aerodynamic characteristics of the wing, with 42 parameters as input data (tapers, aspect ratios, b_m / b) and calculated results were lift, induced drag and airfoil drag distribution [11,13] (by utilizing airfoil database created previously) at 29 characteristic points on the wing for $C_L \in [0,1]$. The program uses five-dimensional matrix to store around 2.2 million relevant numbers. The result of this analysis are the aerodynamic characteristics of the 960 wings. The program creates easy to read diagrams and figures for cruise regime, as well as wings maximum lift coefficient, lift gradient correction, induced drag correction, minimal drag coefficients, lift to drag ratio. It shows that optimal taper and b_m / b depends on the wing's aspect ratio.

Results of the program suggested that it is reasonable to select trapezoid wing as one with the highest aerodynamic efficiency at cruise for this particular case. Fig.8 show the changes in lift to drag ratio at cruise regime.

The results suggest that by increasing the aspect ratio of the wing, the efficiency for the cruise regime is getting better, and the same is happening for the maximal lift to drag ratio, but when using (14) efficiency on cruise regime is getting smaller by unsubstantial amount, while maximal lift to drag ratio is rising as in the previous case. In (14) this is because the friction coefficient is predicted to get a little bit larger than the reduction of induced drag coefficient due to changes in the Reynolds numbers. The results of the program suggest otherwise because data available on aerodynamic characteristics of the selected airfoil suggest insignificant changes to airfoil drag and with reduction in induced drag coefficient, efficiency increases. It has to be emphasized that this is not the case for allpresented wings.

$$C_D = C_{D0} + C_{Di} + 1.2 \cdot C_{D0min} \tag{15}$$

It was decided that wing should have AR ≈ 8.10 based on [3]. The goal was to design wing that would reduce the influence of production imperfections through greater Reynolds numbers. Additional benefits of such wing is better structural integrity since the aircraft is designed to be highly maneuverable, so loading of 4 ÷ 6 G is expected. The preliminary design of the wing was concluded with AR = 8.116, $\lambda = 0.5$, and $b_m/b = 0.0$.

To verify the obtained results, preliminary and detailed calculation of the chosen wing aerodynamic characteristics were conducted. Three methods were utilized. Firstly, the analytical approach was used, for which most of the factors were already calculated by the written program. Other two methods are, DATCOM [15] and CFD [16] calculations. The results are shown in Fig.9. Allmethods show excellent match in both lift and drag characteristics.

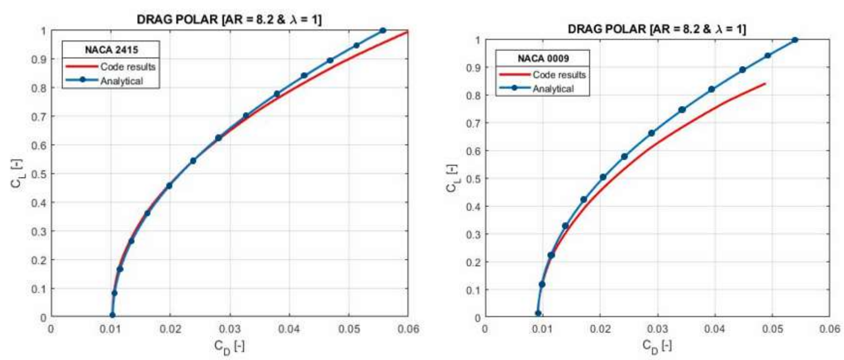

Figure 6. Analytical and written program drag polar results comparison

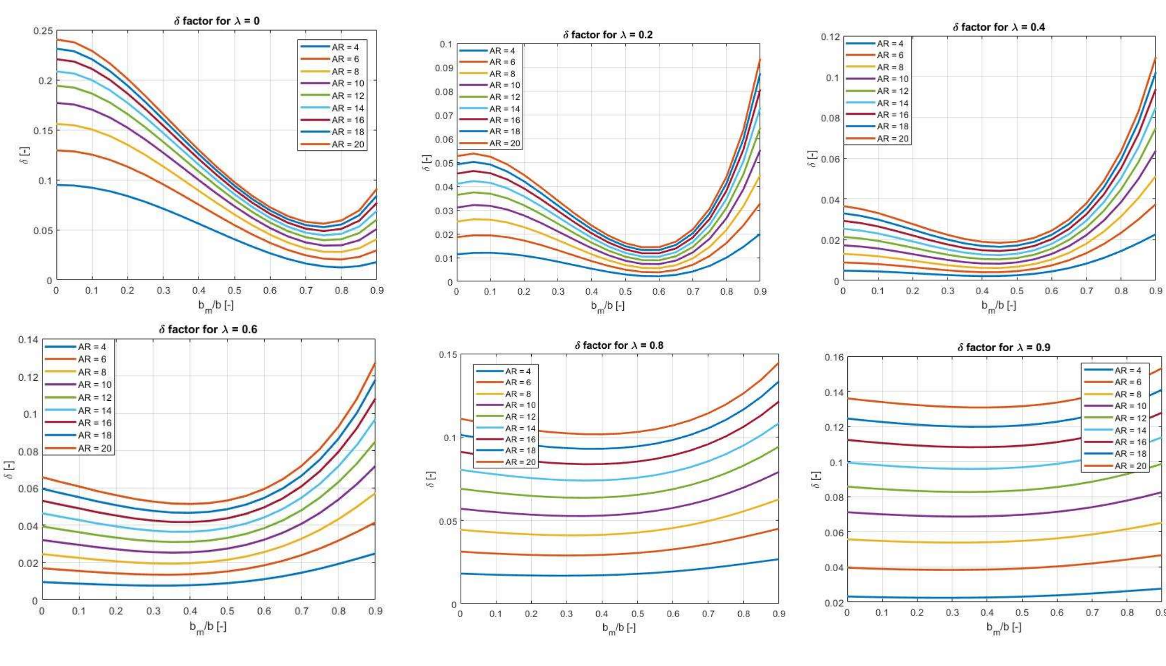

Figure 7. Induced drag coefficient corrections δ

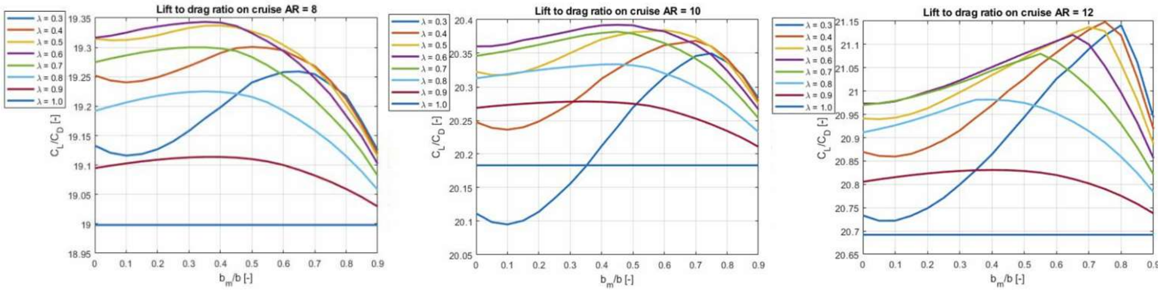

Figure 8. Lift to drag ratio of wings at cruise regime for multiple aspect ratios

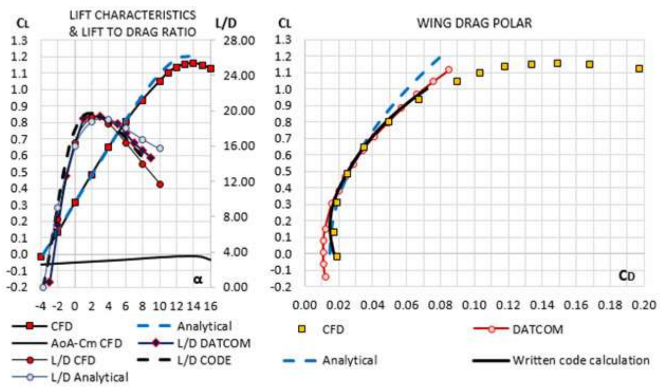

Figure 9. Aerodynamic characteristics of the wing

Preliminary tail surface design

T-shape was chosen as mentioned in the concept design. The reasoning behind this decision is based on reduction of the necessary aerodynamic surface of the horizontal stabilizer because of the downwash reduction due to thehigher position. Thissurface reduction improves aerodynamic efficiency.

To preliminary calculate relative volumes of stabilizers it is necessary to have preliminary design of the fuselage.

Airfoil selected for the aerodynamic surfaces of the horizontal and vertical stabilizers is SD 8020. This airfoil is symmetrical and optimized for low Reynolds numbers. Comparing thechosen airfoil to other symmetric airfoils it is concluded that the chosen airfoil has a clear advantage in aerodynamic efficiency. In accordance with[17] airfoils with $z_5/t > 0.2$ have clear advantage. The chosen airfoil has $z_5/t \approx 0.69$ which indicates that it will have higher maximal lift coefficient than airfoils with lower z_5/t as for example, NACA 0015 which has $z_5/t \approx 0.59$. Downwash calculations are done by utilizing the $\varkappa$- method [1] which accounts forthe positionof the horizontal stabilizer in reference to the center of mass. Also, it takes into the account the wings aspect ratio, span and taper. The relative volume of horizontal stabilizer is $V_H = 0.4497$.

The directional stability was also calculated through standard preliminary methods. The influence of the fuselage was calculated by digitizing data obtained by [18]. The standard calculation procedure was done by analyzing the changes of moment coefficients around the vertical axis with different angles of yaw ψ [18], but additional method used for the verification, utilizing the angle of sideslip β [14,15] and this angle was chosen to be reference as recommended by [1]. The influence of the propulsion system destabilization effect to directional stability as recommended by [1,18,19] was overestimatedin case of this UAV.The relative volume of vertical stabilizer is $V_H = 0.0335$.

For the purposes of verifying the results, Datcom and the Vortex Lattice Method were used (Fig.10). The difference is in that VLM is a non-viscid [14] method and only valid after successful creation of calibration table [20]. Only after that, this method should be used in the linear domain of an aircraft lift characteristics. For preliminary estimation of the stability, table 5was created. The approach for calibration is recommended by [14]. From Fig.10 it is possible to conclude that there is an excellent match of results obtained by utilizing different methods.

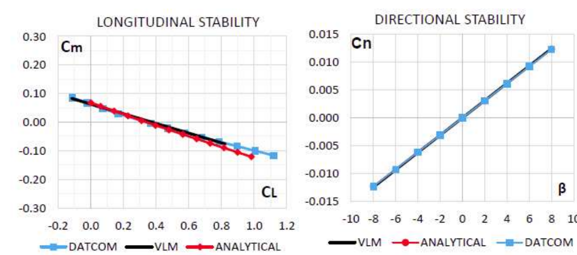

Figure 10. Longitudinal (left) and directional (right) static stability, method comparison

Drag polar prediction

After numerus iterations done in the preliminary design phase so number of parameters could be met, it was imperative to calculate the drag polar of the complete configuration using thepreliminary methods for quicker estimation and complex CFD calculations for result verifications. For the drag estimation of the designed UAV (Fig.11) multiple methods were used. Firstly, the standard preliminary method (1,2) where thecorrection factor $\Delta K = 1.1$ because no air or hybrid cooling wasimplemented,and this factor was simply used for element connection interference. The second method was Datcom [15] and third method was calculated by using a hybrid approach of the mentioned methods with VLM for the induced drag prediction [20,21].

Table 1. VLM calibration table

	Wing	Horizontal stabilizer	Vertical stabilizer
Circualtion	0.953	0.93	0.93
Incidence	0.2915	0.00	0.00
Camber	0.00	0.00	0.00

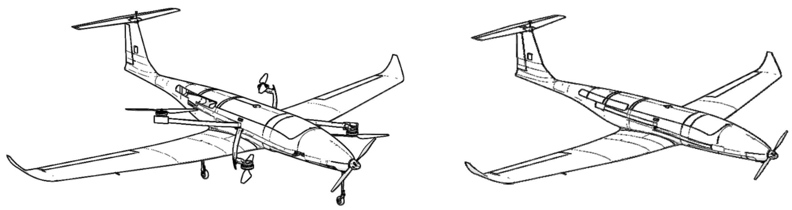

Figure 11. UAV in take-off position (left) and during cruise (right)

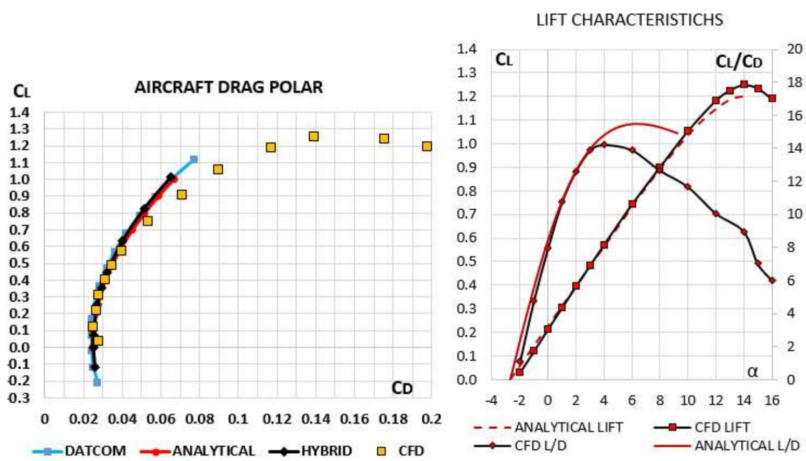

Figure 12. Aerodynamic characteristics of the aircraft; methods comparison

Equation (16) [20] uses Datcom for predicting C_{D0}which is basically drag coefficient at zero lift. This means that the influence of the position of the parasite drag component and induced drag coefficient are almost zero. So even thou the aircraft lift coefficient is zero, the induced drag coefficient is not. VLM predicts $C_{Di} \approx 0.00122$ for $C_L = 0.0$. The analytical method for predicting the position parasite drag was still k = 0.38 for configurations with wing sweep angle $\varphi < 10°$ as recommended by [4,5,20]. VLM was used for predicting induced drag coefficient for the complete configuration.

$$C_D = \left[C_{D0}\right]_{DATCOM} + \left[k \cdot C_L^2\right]_{ANALZYTICS} + \left[C_{Di}\right]_{VLM} \quad (16)$$

For CFD analysis guidelines from [22] were followed. The mesh had about 1,200,000 elements and was optimized on the trailing and leading edges as well as on the wingtips for better prediction of the wingtip vortexes.The turbulence model used for these simulations was k-ε. Fig.12 presents the drag polar data obtained bythe four methods. The aircrafthas $C_{D\ min} = 0.0252$ which represents an aircraft thatbelongs to high performance GA [3]. Lift to drag ratio on cruise regime is $C_L/C_D \approx 11.7$. This ratio could increase with an increase of W/S, but maneuverability of the aircraft would have to suffer.

Conclusion

The design processes vary depending of the complexity of the project and the aircraft. UAV aircrafts can get very complex, depending on their purpose and on systems planned to be implemented. The process of preliminary wing design presented in this paper should increase the speed of conventional wing design to the point where many more iterations, modifications and corrections could be implemented with less time than standard step by step iterationwhile using commercial software. Only symmetric flight configuration had been analyzed, but multiple methods were used for result verification, and shown to have excellent match, even when compared to CFD simulations. CFD with the k-ε turbulence model showed excellent agreement not only with the preliminary drag polar data, but with the analytical lift characteristics.

References

[1] RENDULIĆ,Z.: *Flight Mechanics*, Vojnoizdavački i novinarski centar, Belgrade, 1987.

[2] Gudmundsson Snorri, Embry-Riddle,*General aviation aircraft design: applied methods and procedures*, Aeronautical University 2014.

[3] ŠVORCAN,J., GRBOVIĆ,A.: *Aircraft design – handouts* –University of Belgrade, Serbia, 2019.

[4] KOSTIĆ,I., KOSTIĆ,O.: *Applied aerodynamics – handouts*, University of Belgrade, Serbia, 2019

[5] KOSTIĆ,I.: *Aerodynamic constructions – handouts*, Faculty of Mechanical Engineering, University of Belgrade, 2018

[6] MICHAEL,S.SELIG, JAMES,J.GUGLIELMO, ANDY,P.BROEREN, PHILIPPE GIGUERE: *Summary of Low-Speed Airfoil Data Volume 1*,University of Illinois, 1995

[7] CHRISTOPHER,A.LYON, ANDY,P.BROEREN, PHILIPPE GIGUERE: Ashok Gopalarathnam, Michael S. Selig,*Summary of Low-Speed Airfoil Data Volume 2*, University of Illinois, 1996.

[8] CHRISTOPHER,A.LYON, ANDY,P.BROEREN, PHILIPPE GIGUERE, ASHOK GOPALARATHNAM, MICHAEL,S.SELIG: *Summary of Low-Speed Airfoil DataVolume 3*,University of Illinois, 1997.

[9] MICHAEL,S.SELIG, BRYAN,D. MCGRANAHAN: *Wind Tunnel Aerodynamic Tests of Six Airfoils for Use on Small Wind Turbines*,University of Illinois at Urbana-Champaign Urbana, Illinois, 2003

[10] Gregory A. Williamson, Bryan D. McGranahan, Benjamin A. Broughton, Robert W. Deters, John B. Brandt, and Michael S. Selig,*Summary of Low-Speed Airfoil Data Volume 5*,University of Illinois, 2012

[11] Miroslav Nenadović,*Basics of Aerodynamic Constructions – Airfoils Part 1*, University of Belgrade, “Prosveta”, Belgrade

[12] Raymond F. Anderson,*NACA TR 572 Determination of the characteristics of tapered wings*, NACA 1940.

[13] Ira H. Abbott, Albert E. von Doenhoff, Louis S. Stivers Jr,*NACA TR 824 Summary of airfoil data,* NACA 1945.

[14] ANALYTICAL METHODS, INC., *VLAero+ User’s Manual Version 2.2.5,*Redmond, Washington, 2007.

[15] McDonnell Douglas Astronautics Company / St. Louis Division,*The USAF Stability and Control DATCOM Volume 1, User’s Manual*, Missouri, 1979.

[16] ANSYS, Inc.,*ANSYS Fluent Tutorial Guide*, Southpointe, January 2018

[17] Jan Roskam, C. T. Lan, DARcorporation, Lawrence,*Aircraft Aerodynamics and Performance*, Kansas, 1997.

[18] Courtland D. Perkins and Robert E. Hage,*Aircraft performance stability and control*,John Wiley& Sons, Inc. 1949.

[19] Miroslav Nenadović, *Aircraft Stability and Control Part 1*, University of Belgrade, “Zavod za grafičku tehniku Tehnološko-metalurškog fakulteta”, Belgrade 1981.

[20] Ivan Kostić, Zoran Stefanović, Zlatko Petrović, Olivera Kostić, Abdulhakim Essari, *Hybrid approach in the initial aerodynamic, stability and performance calculations of a light aircraft,* Faculty of Mechanical Engineering, Department of Aerospace Engineering, University of Belgrade, 2013.

[21] Ivan A. Kostic, Zoran A. Stefanovic, Olivera P. Kostic, *Aerodynamic Analysis of a Light Aircraft at Different Design Stages*, University of Belgrade Faculty of Mechanical Engineering, Belgrade, 2014

[22] Zoran Stefanovic, Ivan Kostic, Olivera Kostic, *Determination of aerodynamic characteristics of a light aircraft using viscous CFD modeling,*University of Belgrade Faculty of Mechanical Engineering, Belgrade, 2014

Received: 15.07.2020.
Accepted: 01.09.2020.

Aerodinamički dizajn bespilotne letelice u više faza

Ovaj rad prezentuje metodologiju aerodinamičke optimizacije bespilotne letelice sa VTOL sposobnostima. Letelice kao što su ove obično lete pri malim brzinama, i zbog toga se očekuju mali Rejnoldsovi brojevi. Otpor trenja značajno zavisi od kvaliteta proizvodnog procesa. Prema tome, ukoliko se adekvatni koraci ne preduzmu, javiće se visoki koeficijenti trenja koji mogu drastično da promene performanse letelice. Promene geometrijskih parametara ne utiču samo na indukovani otpor krila, zbog osetljivosti na promene Rejnoldsovog broja utiču i na raspodelu profilnog otpora. Napisan je kod za proračun aerodinamičkih karakteristika krila zarad određivanja optimalnih geometrijskih parametara. Svi neophodni koeficijenti su izračunati korišćenjem Galuertovog rešenja Prantlove jednačine primenjenim na višesegmentna krila. Implementacijom aerodinamičkih koeficijenata brojnih eksperimentalno ispitanih aeroprofila optimizovanim za male Rejnoldsove brojeve, raspodela profilnog otpora, i indukovani otpor krila za veliki broj napadnih uglova su izračunati. Dobijeni rezultati su predstavljeni dijagramima, a metodologija za izbor najefikasnijeg krila je opisana. Dizajn T-oblika repnih površina je izvršen analitičkom metodom, dok su metoda vrtložne mreže, DATCOM, i CFD korišćeni za potrebe verifikacije rezultata.

Ključne reči: **dizajn bespilotne letelice, VTOL, aerodinamički dizajn letelice.**