Reliable method of aerodynamic analysis using computational fluid dynamics and scaled models in the development process of a Very Light Airplane

Aleksander Olejnik¹, Adam Dziubiński² and Łukasz Kiszkowiak¹

¹ Military University of Technology, Faculty of Mechatronics, Armament and Aerospace, 2 gen. Sylwestra Kaliskiego Str., 00-908 Warsaw, Poland
² Lukasiewicz Research Network – Institute of Aviation, Aerodynamics Department, Al. Krakowska 110/114, 02-256 Warsaw, Poland

Corresponding author: lukasz.kiszkowiak@wat.edu.pl

Abstract. In past decades a massive improvement of computational fluid dynamics (CFD) methods and the rapid increase of computational resources made it possible to simulate a lot of phenomena appearing during the flow of fluid around objects. In following paper a reliable method of aerodynamic analysis using both CFD and scaled models in the development process of a Very Light Airplane have been presented. A method of preparing a numerical model of an airplane and the aerodynamic analysis methodology have been shown. A numerical calculations using finite volume method implemented in specialized software were performed. What is more important, to perform the aerodynamic tests in wind tunnels, scaled models of an airplane have been prepared using the modern and fast manufacturing technologies, including 3D printing and CNC machining. The results have been shown in the graphs form of aerodynamic force and moment components as function of angle of attack. During research an influence of structural parts of an airplane on aerodynamic characteristics have been analyzed. The qualitative results of a flow around the aircraft body have been presented in form of parameter distribution maps on the airframe surface have been shown. Visualization of pressure distribution have been extended with path lines visualization of the flow. The research described in the paper is an example of professional and innovative approach to the subject matter.

1. Introduction

The article presents the results of aerodynamic analyzes carried out during the development of the OSA (in English WASP) aircraft. Design of the aircraft was carried out with the use of modern computer-aided design (CAD) system and support of the product lifecycle: Siemens NX, ANSYS and MSC.Patran/Nastran. These programs allow to conveniently work with dynamic scale model, identify inconsistencies in the design and make the necessary changes in order to minimize costs, definition performance, create working construction documentation [1, 2].

Dynamic development of microprocessor technology and methods of Computational Fluid Dynamics has enabled the simulation of many phenomena occurring during the flow of liquids around solid bodies. CFD is a branch of fluid mechanics focused on detailed analysis and modeling of flows using numerical methods. The set of differential equations describing the movement of liquids and gases in
general case can be solved only by use of numerical methods such as finite volume methods. One of the most commonly used packages for solving engineering problems in the field of fluid mechanics and aerodynamics is the ANSYS Fluent software [3] based on solving partial differential equations using the Finite Volumes Method. It enables analysis of incompressible and compressible flows, with optional consideration of flow viscosity. Many turbulence models have been implemented in this program. Motion equations are solved on non-structural (tetrahedral), structural and hybrid meshes [3, 4].

On the other hand the basic aerodynamic characteristics of a newly-designed aircraft are obtained from tunnel tests of geometrically reduced model. To perform aerodynamic tests in wind tunnel, scaled models of an aircraft using fast prototyping methods and 3D printing have been prepared. Wind tunnels tests are used to validate the performance of new aircraft designs, long before the aircraft can actually fly. There are many advantages of using scale models in comparison to real airplane tests. Important arguments taken into consideration are low costs and guaranteed safety of researches [5, 6].

The research object OSA is an airplane that belongs to a Very Light Aeroplanes category. Due to its versatility it can be used by the army, Border Guard, Fire Brigade and other Public Security Forces to patrol and monitor events that threaten public safety [7]. The concept of the OSA airplane consists in adopting an unconventional aerodynamic and structural configuration that guarantees visibility from the cabin comparable to a helicopter, the use of lightweight strength structures, and the ability to operate from not prepared airfields. Its properties are comparable to or better than those of modern aircraft of this type. The spacious cabin accommodates a crew of two and provides almost unrestricted visibility at a helicopter level. OSA airplane performance like range and flight duration significantly exceed the helicopters used by the Police. Basic technical specifications are as follows:

- Wing span $b = 9$ m
- Length $l = 5.73$ m
- Wing Area $S = 10.8$ m$^2$
- Maximum Take-off Weight $W_{\text{max}} = 750$ kg
- Cruise Speed $V_H = 240$ km/h
- Rate Of Climb $V_p = 8$ m/s

![Figure 1. Developed OSA patrol aircraft](image-url)
2. Development of numerical models of the aircraft for CFD analysis

To generate the computational meshes ICEM CFD software [8], which is part of the ANSYS package, was used. The ICEM CFD enables the development of structural and non-structural meshes with tetrahedral, prismatic, hexagonal, pyramidal as well as hybrid meshes consisting of many types of elements. In the area surrounding a given airframe, a non-structural mesh was generated with the densities shown in Figure 2. The size of the computational mesh for the OSA aircraft was about 6 million cells. Five layers of prism cells simulating the boundary layer were generated around the walls of the aircraft. The thickness of the first mesh element (0.6 mm) corresponded to the turbulence parameter y+ in the range <30 - 200>, which is recommended for the Spalart-Allmaras turbulence model used. This model is adopted as a standard in the analysis of external flows, especially in the range of Reynolds numbers used in aviation [3].

For performing numerical aerodynamic analyzes in symmetrical flow around an object, the following assumptions were made:

- symmetry of the flow field;
- symmetry of geometry;
- the flow is stationary and stable, i.e. there is neither Karman vortex path behind the airframe nor any other non-stationary structure in the flow;
- flight conditions correspond to the zero altitude (at the sea level) according to the reference atmosphere: pressure p=101325 Pa, temperature T=288.15 ºK, and air density $\rho=1.225 \text{ kg/m}^3$.

3. Development of scaled models of the aircraft for wind tunnel tests

To perform aerodynamic tests in wind tunnel, scaled models of an aircraft using fast prototyping methods and 3D printing have been prepared. The use of a specific technology of develop a scaled model is dictated by its size and the purpose or type of research in which the model will be used. Currently, additive manufacturing methods are very popular. There are numerous attempts to use these methods in development process of aircraft scaled models. However, one cannot forget about the technologies of develop scaled models with the use of elements made on computer numerical control machine tools. Scaled models prepared for wind tunnel tests should be characterized by high stiffness. However, in the case of scaled models for flight tests, the mass and strength criteria are equally important also. Such a model should also have appropriate inertial characteristics. Thus, its design process is very similar to designing a real-scale aircraft. For this reason, the develop process is more complicated and time-consuming. Different technologies are applied during the production of details of composite materials which are different in complexity, cost, and equipment. The selection of a
technology is conditioned to the volume of production, the degree of preparation and economic evaluation of production efficiency [9, 10]. Figure 3 shows developed OSA 50% scaled model and its construction details. A fiberglass and honeycomb sandwich composite is used to form the fuselage. The wings and empennage are fabricated from carbon fibers composite and carbon sandwich construction to make possible a high load carrying capability and light weight. Duraluminium is used sparingly in such places as the wing/pylon mount, the spin recovery system, and landing gear components.

![Figure 3. Developed OSA 50% scaled model (a) and its construction details (b)](image)

4. Quantitative and qualitative results

During aerodynamic analysis, the right-handed Cartesian coordinate systems were used [11]. Local (airframe) coordinate system is defined as follows: its center appears in a center of mass of the aircraft. The Oxz datum plane is a plane of aircraft's geometrical, inertial and aerodynamical symmetry. Ox axis belongs to the airframe's symmetry plane, is a main inertial axis and is directed forward. Oy axis is perpendicular to the symmetry plane and is directed right from symmetry plane, along with right wing. Oz axis also belongs to the symmetry plane, is perpendicular to both others and is directed down.

An aerodynamic coordinate system was defined in a following way:
- center in the same point "O" as the local coordinate system;
- Oxa axis is directed along the velocity vector;
- Oza axis belongs to the symmetry plane of the aircraft;
- Oya is perpendicular to both axes, and is directed as for the right-handed coordinate system, to the right wing.

Moreover angle of attack \( \alpha \) was defined as an angle between the velocity vector \( V \) projected on the symmetry plane of the aircraft and its longitudinal Ox axis. The following formulas [12] were used to find the aerodynamic coefficients:

- drag force coefficient
  \[
  C_D = \frac{2 \cdot F_D}{\rho \cdot v^2 \cdot S}
  \]  
- lift force coefficient
  \[
  C_L = \frac{2 \cdot F_L}{\rho \cdot v^2 \cdot S}
  \]  
- pitching moment coefficient
  \[
  C_m = \frac{2 \cdot M}{\rho \cdot v^2 \cdot S \cdot MAC}
  \]
where:
\[ F_D \] – drag force [N]; \[ F_L \] – lift force [N]; \[ M \] – pitching moment [Nm]; \[ \rho_\infty \] – air density [kg/m\(^3\)]; \[ v_\infty \] – undisturbed flow velocity [m/s]; \[ S \] – lifting surface [m\(^2\)]; \[ MAC \] – mean aerodynamic chord [m].

Figures 4 ÷ 6 show a comparison of the aerodynamic characteristics obtained as a result of:
- numerical aerodynamic analysis of:
  - aircraft with a V-type tail (OSA V);
  - aircraft without tail section (OSA VBU);
- wind tunnel tests of:
  - aircraft with a V-type tail (OSA VT);
  - aircraft without tail section (OSA VIBUT);

Wind tunnel tests were carried out in the Institute of Aviation Wind Tunnel T-3 (\( \varnothing 5\)m) in order to determine aerodynamic characteristics for the OSA 50\% scaled model. The tests were carried out for an air stream velocity of approx. 28 m/s. The selected speed corresponded to a dynamic pressure \( q = 50 \) [kgf/m\(^2\)]. The air stream turbulence coefficient in the tunnel measuring space was \( TF = 1.22 \). The effective Reynolds number (the “Re” number after its multiplication by the turbulence coefficient), related to the mean wing aerodynamic chord was about \( Re_{ef} \approx 1.54 \) million. Aerodynamic characteristics were measured using a 6-component aerodynamic strain gauge balance in the range of angles of attack \( \alpha = -10^\circ \pm 30^\circ \). The strain gauge balance was installed inside the fuselage of the aircraft model. The model of the OSA aircraft was mounted in the tunnel measuring space on a mast with a rear support to change the angle of attack.

![Figure 4. Comparison of the experimental and numerical drag force coefficient characteristics for the OSA aircraft with a V-type tail](image-url)
Figure 5. Comparison of the experimental and numerical lift force coefficient characteristics for the OSA aircraft with a V-type tail.

Figure 6. Comparison of the experimental and numerical pitching moment coefficient characteristics for the OSA aircraft with a V-type tail.
The characteristic of the drag force coefficient shows that the impact of the tail section on the value of this coefficient increases with the increase of the angle of attack. A similar tendency occurs in the lift force coefficient characteristics. As the angle of attack increases, the influence of the tail section on the value of the lift coefficient increases. On the other hand, on the characteristics of the pitching moment coefficient, we can observe that subtracting the tail section causes large changes in airplane stability. It has to be mentioned that the characteristics obtained in numerical analyzes overlap with those obtained from wind tunnel tests in the small angles of attack range. The largest discrepancies are found in the values of the pitching moment coefficient obtained for the aircraft without horizontal tail. It is caused by small differences in the position of the aerodynamic pole in the numerical analyzes and wind tunnel tests. Moreover, slight discrepancies in the characteristics of the lift force coefficient and the drag force coefficient occur for higher angles of attack exceeding the angle of attack $\alpha = 15^\circ$. One of the reasons for these discrepancies is the method of modeling the phenomenon of flow detachment in the applied numerical method.

Figure 7 presents a qualitative results obtained for selected angle of attack in the form of pressure map and flow detachment areas with streamlines shown on the surface of the airframe. The presented visualization method has an advantage of combining the pressure information in a given area of the airplane (or any other scalar physical variable distribution, for that matter) with the speed and direction of flow in that area. The areas of separation, i.e. the areas of reverse flow, were depicted using the friction coefficient component along the aircraft axis. The coloring areas have been trimmed so as to color only the surfaces where the flow is in the opposite direction to the undisturbed flow.

![Figure 7. Visualization of pressure distribution and flow detachment areas with streamlines on the OSA aircraft outside surface for angle of attack $\alpha = 22^\circ$.](image)

5. Conclusions and final remarks

A number of numerical analyzes and wind tunnel tests were carried out to possess necessary and important information regarding to aerodynamic properties of newly design airplane. Calculations were performed using the finite volume method, with specialized software and a high-performance computing cluster. Both quantitative and qualitative results were obtained. The values of force and moment were calculated as a function of angle of attack. Based on performed research some additional conclusions have been withdrawn:

− using the Computational Fluid Dynamics method, it is possible to determine the aerodynamic characteristics of Vety Light Airplanes;
− the use of additive and CNC manufacturing methods accelerates the development of a scaled model;
− modifications to the numerical model are simpler and faster than the model of a scaled plane prepared for experimental tests.
− wind tunnel tests allow for relatively quick obtaining of qualitative and quantitative results allowing the verification of the aerodynamic layout of the tested object and the verification of the numerical analyzes results.

Al last but not least, it is worth to mention the high comparability of the obtained numerical results with the results of experimental research proves the correctness of the research methodology presented in this paper.

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