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# The use of Computational Fluid Dynamics methods to improve aerodynamic properties of a newly designed twin-jet engine aerial target

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**Abstract**
The main purpose of this work was to improve aerodynamic properties of newly designed twin-jet engine aerial target using Computational Fluid Dynamics methods. Aerodynamic analysis was performed with specialized software based on solving partial differential equations using the Finite Volumes Method. The aerodynamic analysis results were presented in the form of diagrams showing aerodynamic force and moment components as a function of the angle of attack. In addition, qualitative results of the flow around the plane have been presented. The analysis results leads to the changes in a shape of the airplane and its tail configuration.

## 1. Introduction

The design process of an airplane that meets the imposed criteria in the set of acceptable solutions controlled by the constraints resulting from the planned missions is a complex process. It is inevitable in the design process, that the assumptions made at the beginning do not meet the expectations in terms of the “perfection” of airplane's aerodynamic layout. Such a phenomenon forces to change the shape of airframe and assume better value of its parameters, and proceeding to the next iteration of the design process [1 – 3]. In recent years the development of new, more reliable tools for "multiphysics" calculations allowed the designers to address more problems at the very beginning (or at early stages) of the design process [4, 5]. The authors decided to use an ANSYS Fluent v.15 software [6] based on solving partial differential equations using the finite volumes method [7, 8]. Various science papers [9 – 13] show the possibilities for using numerical methods to possess overall information regarding the aerodynamic characteristics of aircraft or its parts. Worth of mentioning is also, that such a method can be used in further design, starting from the influence of deflected control surfaces, influence of the propeller, and even the cooling systems of the engine and cabin could be tested [14 – 17]. Also the armament drop safety can be tested [18 – 20] in order to avoid contact with the fuselage or other part of the aircraft.

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 [21, 22].

The main purpose of this work was to improve aerodynamic properties, using Computational Fluid Dynamics methods, of newly designed twin-jet engine aerial target shown in Figure 1. The research object was a prototype of an aerial jet target with a programmable flight route OCP-JET 2 intended for training and performance of missile as well as artillery and missile shootings from anti-aircraft sets using radar beam.

Specifications, general characteristics and performance of the twin-jet engine aerial target:

- wingspan: 2.85 m

DOI: 10.13009/EUCASS2023-157



- length: 3.56 m
- wing area: 1.35 $m^2$
- wing aspect ratio: 6.02
- maximum take-off weight: 86.6 kg
- minimum take-off weight: 43.2 kg
- maximum wing loading: 64.15 $kg/m^2$
- mean aerodynamic chord: 0.459 m
- maximum speed: 504 km/h
- operational altitude: 100 ÷ 5000 m
- maximum load factor: 10
- duration of flight: 60 min
- thrust: 284 N
- launch type: catapult
- landing: parachute

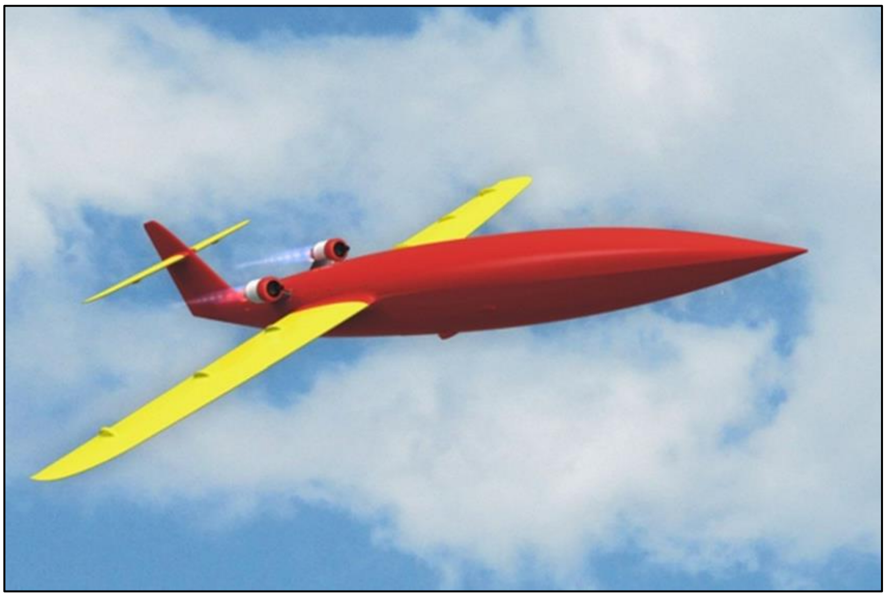

Figure 1: The visualization of a newly designed twin-jet engine aerial target OCP-JET 2

## 2. Development of numerical models of the aircraft for CFD analysis

The use of Computational Fluid Dynamics methods at the stage of designing the airplane aerodynamic layout significantly accelerates the implementation of the project at particular stages of the design spiral. Moreover, it speeds up the variation process and facilitates the evaluation of further project development. The design process of an airplane aerodynamic layout at the stage of conceptual design and preliminary design must be preceded by a stage of assumptions and determination of the most important criteria, the fulfilment of which is a necessary condition in the subsequent stages of aircraft design [23 – 25]. The geometry of an OCP-JET 2 aircraft during design has been changing, especially on its tail area. The complicated tail with three vertical surfaces has been changed into classic tail configuration, and whole tail has been moved backwards. The wing also changed its shape, especially in the area of wing-fuselage intersection. Filleted intersection has been removed as it does not introduce much improvement in the drag and begin of the flow separation on the wing, it just increases the wetted area. Usually for the mid-wing configuration the wing rarely has a filleted intersection with the fuselage, as the fuselage's wall is perpendicular to the wing and fillet does not help, it rather decreases a stall angle and the separation in this area appears on the lower angle of attack. The main differences between the preliminary and final design geometry were shown in Figure 2.
To generate the computational meshes ICEM CFD software [26], 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 3. Five layers of prism cells simulating the

DOI: 10.13009/EUCASS2023-157



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 [7].

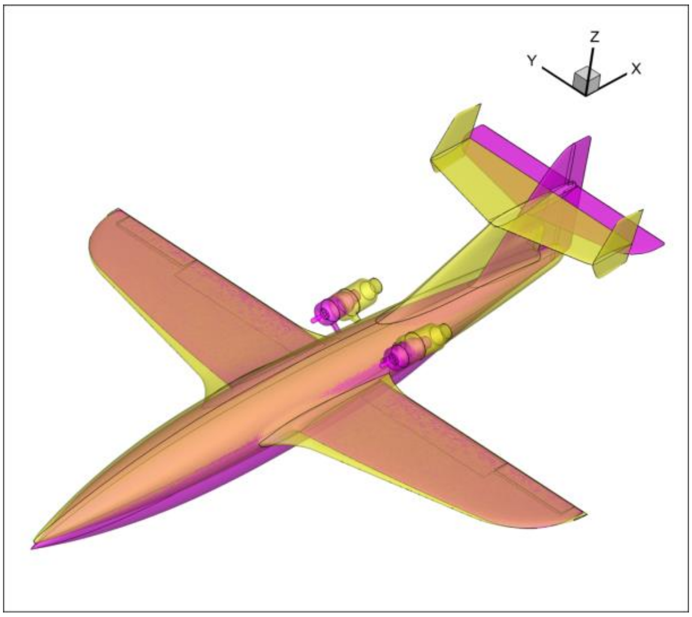


Figure 2: Comparison between preliminary and final design geometry of OCP-JET 2 aircraft

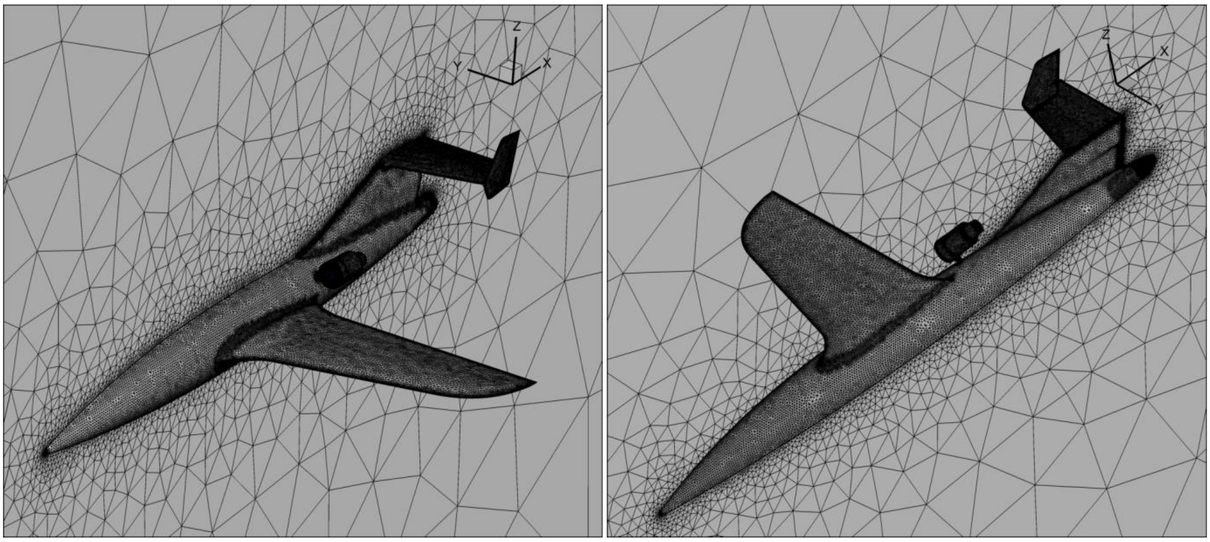

Figure 3: The computational mesh density around the OCP-JET 2 aircraft

To perform numerical aerodynamic analyzes in symmetrical flow, 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 K, and air density $\rho$=1.225 kg/m$^3$.

The position of the pole of the aerodynamic moment was on the plane of symmetry of the aircraft at the point corresponding to the projection of the 0.25 SCA point on this plane.

DOI: 10.13009/EUCASS2023-157



Usually the airframe is divided into the named zones in order to obtain, except summary force and moment components, also forces and moments on the specific parts of the airframe. The division usually is corresponding with the way, that the airframe is divided into its technological parts. This way the design team obtains clear information on forces and moments acting on any specific parts and loads on their mounting points are much easier to estimate. Therefore, due to the adopted method for presenting the results of the calculations, the surfaces of the aircraft were divided into appropriate zones, which are shown in Figure 4.

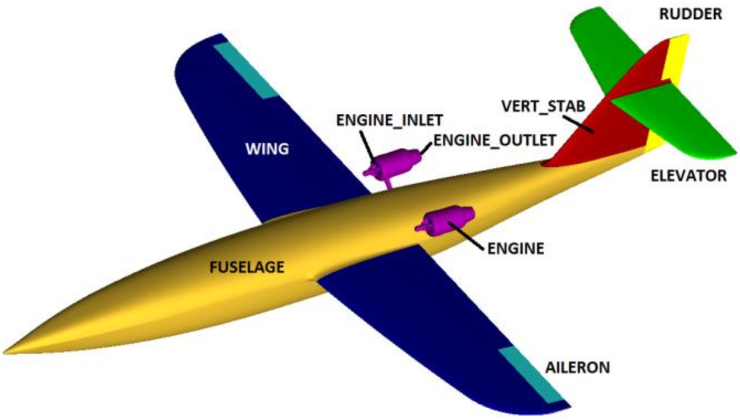


Figure 4: Division of the aircraft airframe surfaces into appropriate computational zones

## 3. Development of scaled model 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.

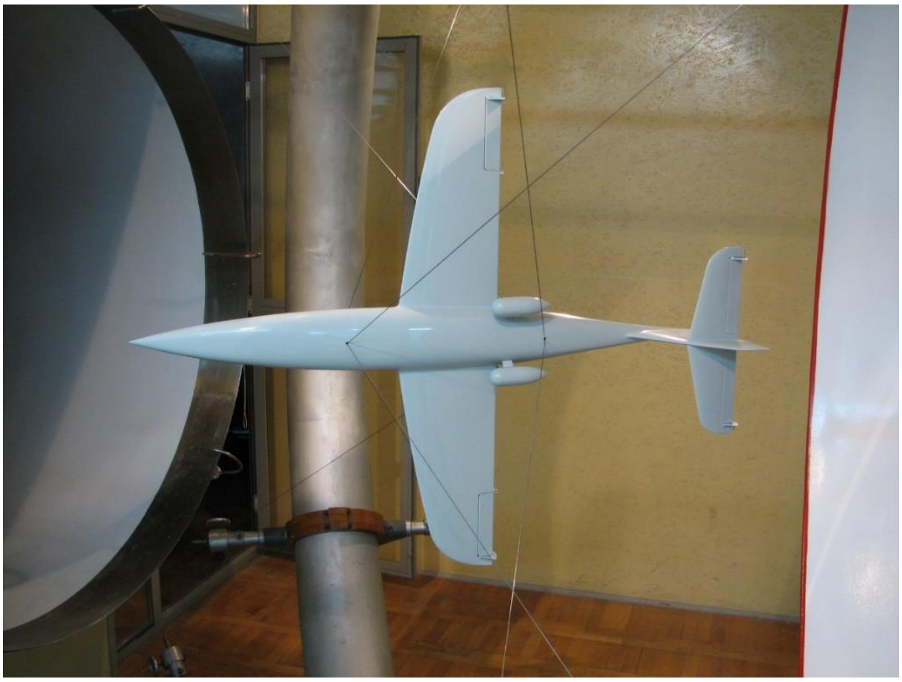

Figure 5: The scaled model of OCP-JET 2 aircraft in test section of low-speed wind tunnel

DOI: 10.13009/EUCASS2023-157



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 [4, 10]. Figure 5 shows 25% scaled model of OCP-JET 2 aircraft in test section of low-speed wind tunnel.

## 4. Results and discussion

During aerodynamic analysis, the right-handed Cartesian coordinate systems were used [7, 8]. 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 α was defined as an angle between the velocity vector V projected on the symmetry plane of the aircraft and its longitudinal Ox axis. Figure 6 shows the aircraft size, coordinate systems position, positive directions of forces and angle of attack α.

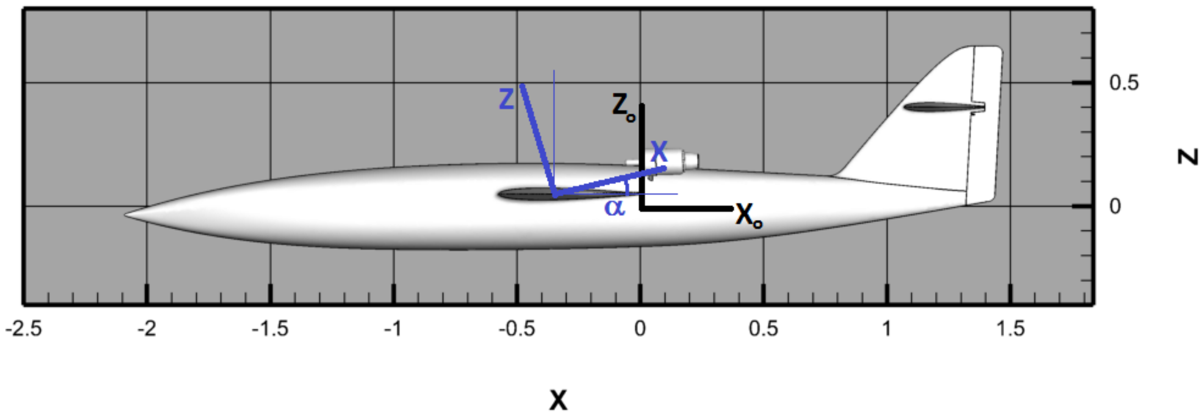


Figure 6: The coordinate systems position, positive directions of forces and angle of attack [dimension in meters]

The following formulas [7, 8] were used to find the aerodynamic coefficients:

- drag force coefficient

$$C_D = \frac{2 \cdot F_D}{\rho_\infty \cdot v_\infty^2 \cdot S} \tag{1}$$

- lift force coefficient

$$C_L = \frac{2 \cdot F_L}{\rho_\infty \cdot v_\infty^2 \cdot S} \tag{2}$$

- pitching moment coefficient

$$C_m = \frac{2 \cdot M}{\rho_\infty \cdot v_\infty^2 \cdot S \cdot MAC} \tag{3}$$

where:

$F_D$ – drag force [N];

DOI: 10.13009/EUCASS2023-157



$F_L$ – 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 7 ÷ 9 show a comparison of the results of experimental tests and numerical analysis in the form of aerodynamic characteristics presented as a function of the angle of attack obtained for the preliminary design (marked as CFD OCP-JET 2 PD) and final design (marked as CFD OCP-JET 2 FD) of the OCP-JET 2 aircraft. The drag force is slightly lower for the new version, also small constant decrease appeared in lift force coefficient, but the stall region is much smoother than the previous one. The lif force coefficient characteristics show an earlier stall condition in inverted flight. The maximum value of the lift force coefficient $C_{Lmax}$ for the final design version of OCP-JET 2 is obtained at α=14° compared to 10° for the older version of the aircraft. Aerodynamic moment is more symmetric in comparison to angle of attack, but derivative dCm/dα value has higher absolute value, which means that the aircraft is more stable in pitch, and this is effect of increasing the tail length.
The results of numerical analysis were compared with the results of experimental tests (marked as WT OCP-JET 2 FD) carried out in a low-speed wind tunnel of the Institute of Aeronautics of the Faculty of Mechatronics, Armament and Aviation of the Military University of Technology. The tests were carried out for the 25% scaled model of final design version of OCP-JET 2 aircraft. The tests were carried out for an air stream velocity of approx. 30 m/s. The selected speed corresponded to a dynamic pressure q = 500 Pa. The effective Reynolds number related to the mean wing aerodynamic chord was about Re = 20700. What draws attention, is the large conformance of the results obtained in the numerical analysis with the results of experimental tests. This indicates the correctness of the developed numerical model of the OCP-Jet aircraft for the needs of aerodynamic analysis. Small differences in values of individual aerodynamic coefficients result directly from the specifics of the conducted experimental tests, among others from different values of criterion numbers.

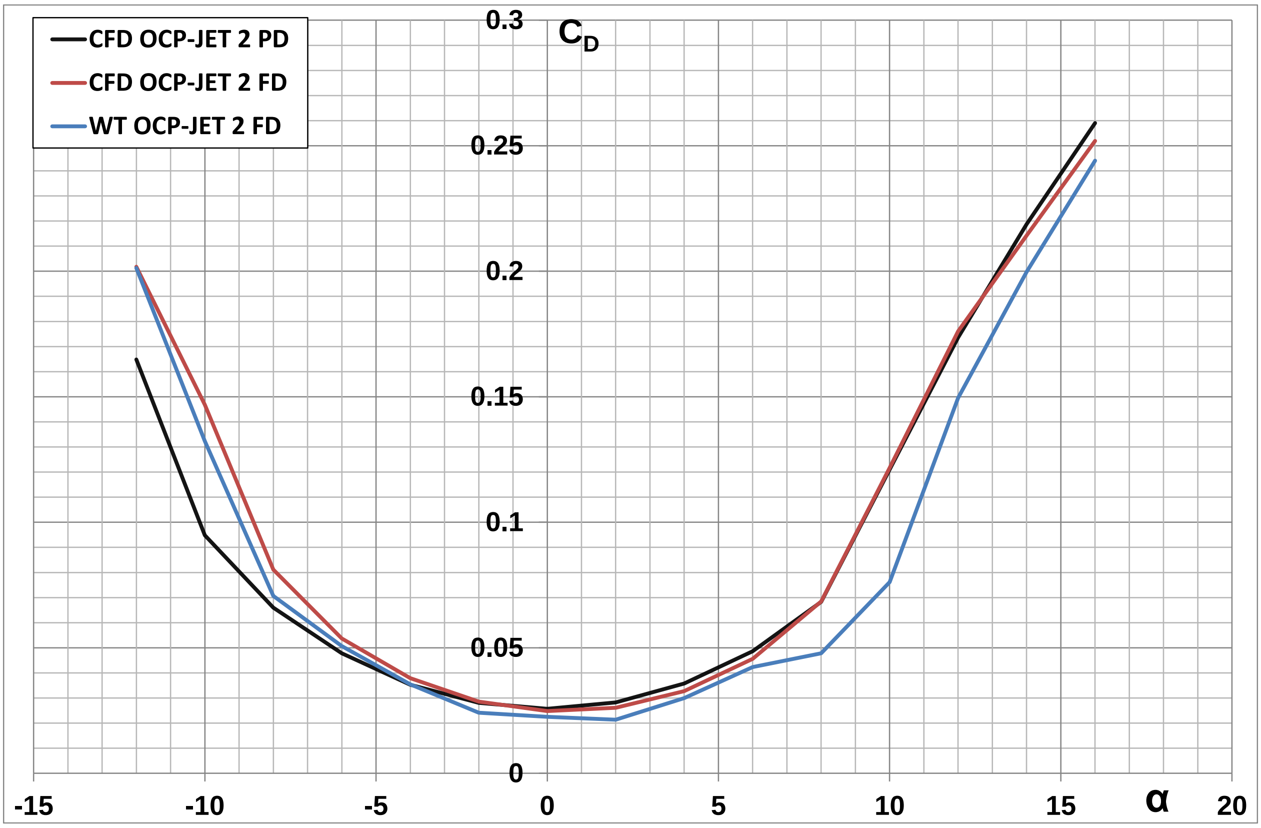


Figure 7: Comparison of drag force coefficient for the preliminary and final design of the OCP-JET 2 aircraft

DOI: 10.13009/EUCASS2023-157



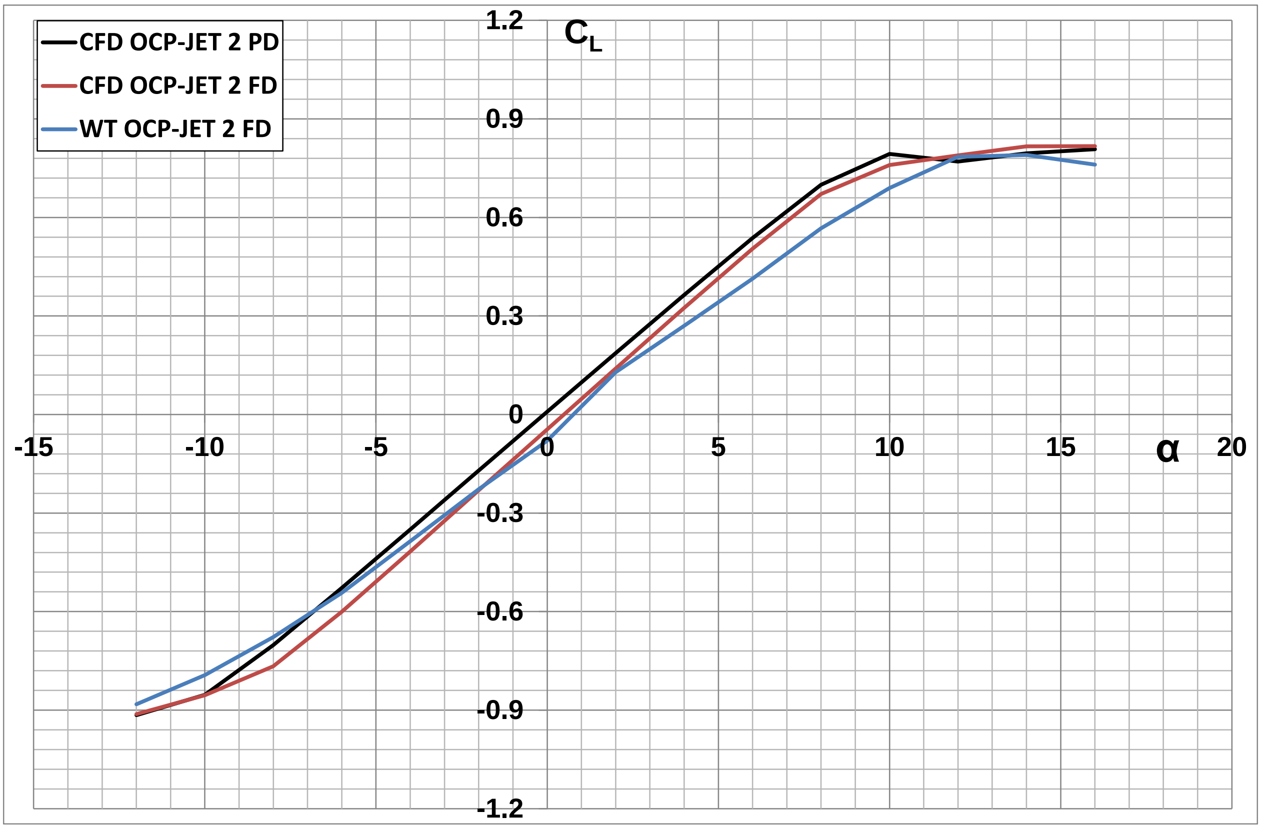


Figure 8: Comparison of lift force coefficient for the preliminary and final design of the OCP-JET 2 aircraft

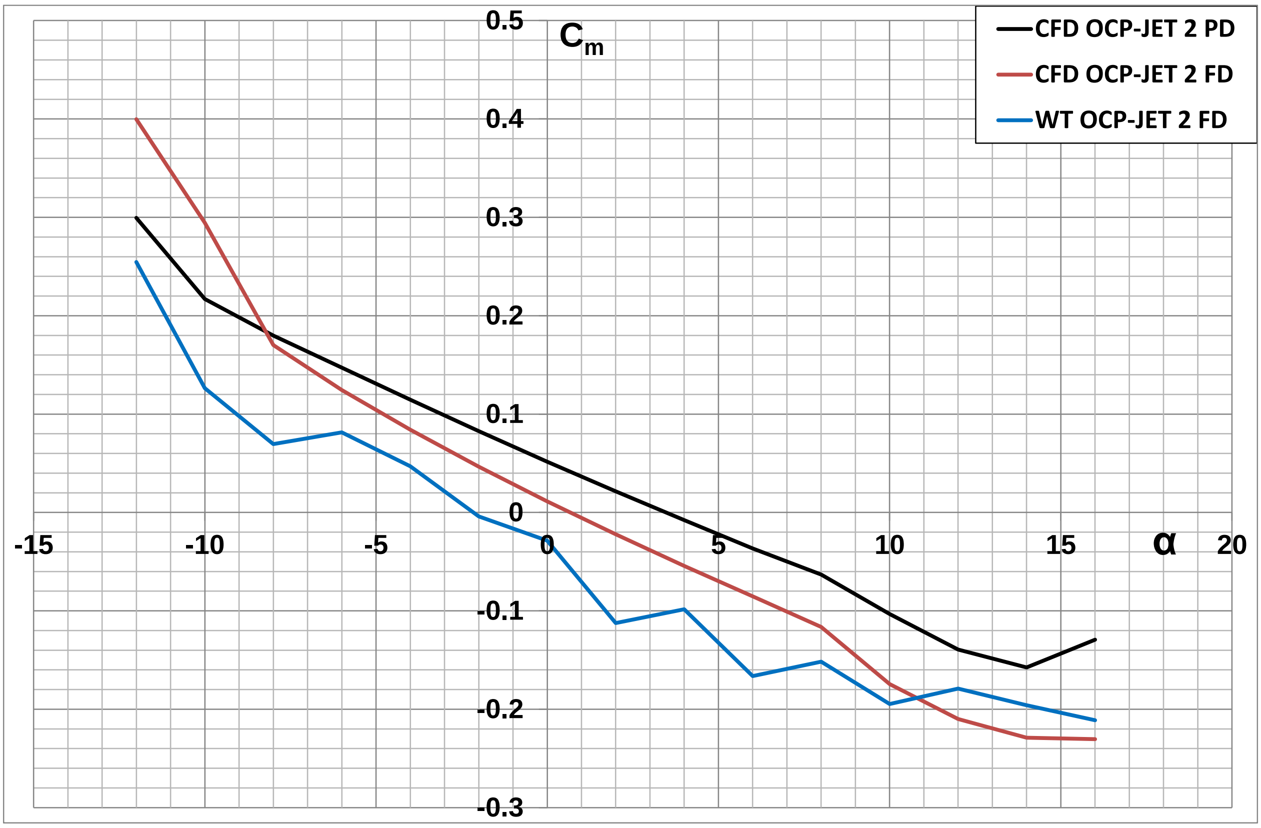


Figure 9: Comparison of pitching moment coefficient for the preliminary and final design of the OCP-JET 2 aircraft

DOI: 10.13009/EUCASS2023-157



Figure 10 presents a qualitative comparison of the results obtained for selected angles of attack in the form of a pressure map with pathlines shown on the surface of the final design version of aircraft. In the presented drawings it can be seen that as the angle of attack increases, the negative pressure area on the upper surface of the wing increases. For smaller angles of attack, the negative pressure area is formed at the leading edge of the wings. As the angle of attack increases, the negative pressure area on the wing surface gradually increases. Flow separation on the wing starts quite early, at 8º angle of attack, but only on the leading edge of the outer wing. At α=12º, there is already a reverse flow over the entire wing beyond the wing tip. A stable flow on the horizontal tail is maintained for a very long time, there was no flow separation in the entire tested range. At α=12º, we observe a flow separation on the engine nacelle, with the detachment starting at the rear step of the housing near the exhaust nozzle.

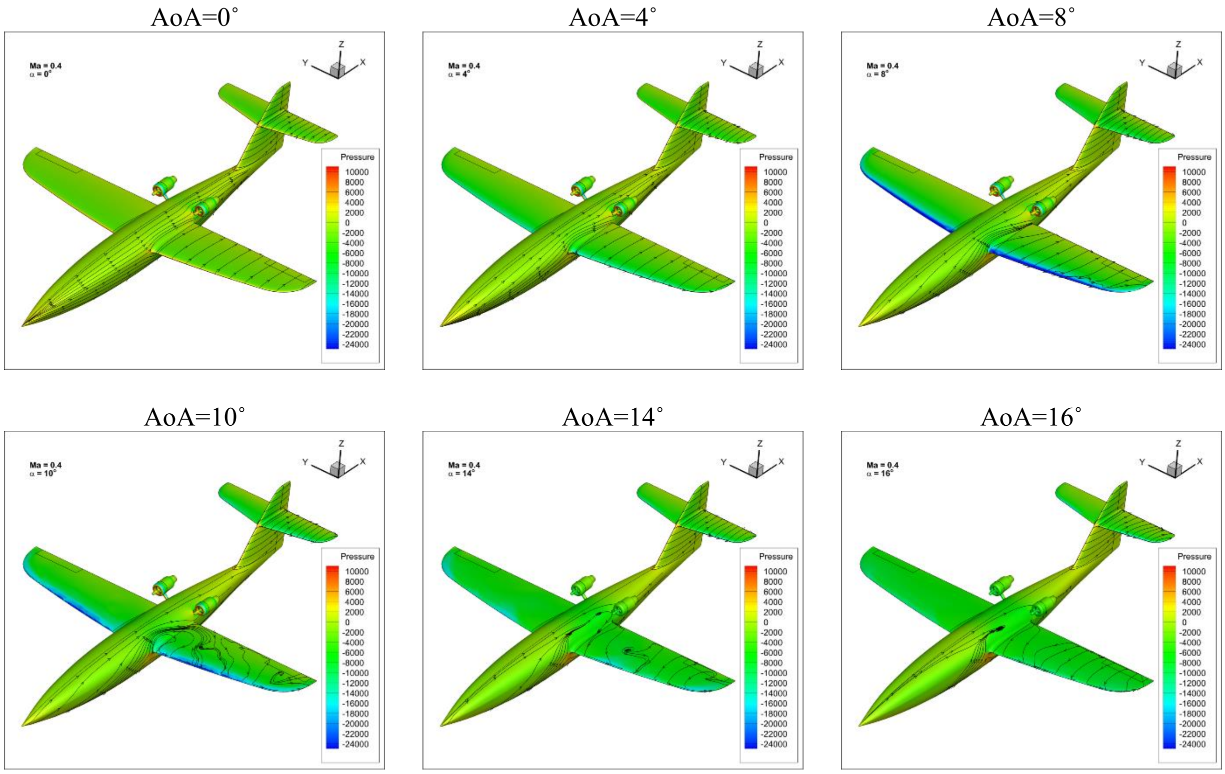


Figure 10: Presentation of changes in the pattern of pathlines on the surface of the aircraft with visualization of pressure distribution for various values of the angle of attack

## 4. Conclusion and final remarks

The main purpose of this work was to improve aerodynamic properties, using Computational Fluid Dynamics methods, of newly designed twin-jet engine aerial target. What is more, considering the high maneuverability of this aerial vehicle, it is extremely important to know this type of data during design process. The CFD is an efficient tool to obtain information on the design impossible to obtain otherwise, especially when the model is divided into zones. Ability to calculate the forces, moments and to check the stability and separation areas are much cheaper, does not demand very expensive tests with divided model equipped with a set of balances, equipment, flight tests for stability and other demands before even the first element of the airframe is produced. Of course, the simplified models and experience, used till this days is reasonable set of tool, but using CFD, which becomes cheaper every year, allows to have much better first approximation of the design, and introduce big changes earlier in the design process, which is much less problematic than in the end of the design loop. The obtained results will have a significant impact on the decisions of the research team regarding the final shape of the airplane being developed. Therefore, the process of using the aerodynamic characteristics as the leading conclusion in changes of the design has been shown in this paper.
At 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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