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THE USE OF REVERSE ENGINEERING AND COMPUTATIONAL FLUID DYNAMICS METHODS IN THE PRELIMINARY DESIGN OF A LOW COST SATELLITE LAUNCH SYSTEM

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Abstract

The authors proposed the development of a unique low-orbit launch system based on a system consisting of a carrier aircraft and a space rocket orbiter. The main purpose of this work was to obtain, using Reverse Engineering and Computational Fluid Dynamics methods, a reliable information on aerodynamic properties of a carrier aircraft and a space rocket orbiter assembly. Aerodynamic properties of launch vehicles also affect the vehicle's trajectory. Therefore, it is extremely important to know the reliable aerodynamic characteristics of the airplane - rocket assembly. Moreover, the applied method allows the analysis of the influence of individual elements of the assembly on aircraft aerodynamic properties. The numerical geometry of the aircraft carrier was developed as a result of the digitization process of real aircraft outer surface. A reliable geometric model was obtained, characterized by high accuracy of mapping the aircraft's surfaces. In order to prepare the numerical model of the aircraft for aerodynamic analyzes, it was required to introduce appropriate corrections in the obtained surface geometry enabling the generation of the computational mesh. In past decades a massive improvement of computational fluid dynamics methods and the rapid increase of computational resources made it possible to simulate a lot of phenomena appearing during the flow of fluid around object. Aerodynamic analysis was performed using 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. What is more, in order to confirm the correctness of the chosen method the obtained results have been compared with the results of experimental tests carried out in the wind tunnel. It will also prove that adopted method is sufficient for solving this type of problems.

Keywords: mechanics, aerodynamics, computational fluid dynamics, satellite launcher

1. Introduction

At the beginning it should be clearly emphasized that air launch spacecraft have numerous advantages over traditional vertical launch configurations. For various countries it can be only way to achieve the capabilities to take science or communication microsatellites into low Earth orbit (LEO). What is more, the ATK Orbital company (now Northrop Grumman) has been using the Lockheed L-1011 Tri Star airliner as a carrier aircraft for this purposes since the 1990s [1]. In 2006, Boeing presented [2] the concept of launching a space rocket on the back of a Boeing F-15 supersonic combat aircraft as an alternative Responsive Air Launch system to the "classic" rocket launching from Earth. Similar systems were analyzed and discussed in later works [3, 4, 5, 6, 7, 8, 9], where supersonic airplanes were proposed as a carriers and launch platforms of space rockets, e.g. F-16 [5] or MiG-31 [9]. Currently, the aviation of the Polish Armed Forces is withdrawing from use MiG-29 and Su-22 planes, which can be used as Responsive Space Assets.

At present, Poland does not have any system for launching loads into Earth's orbit. The ability to take microsatellites or nanosatellites into LEO is the main reason why Poland does not have neither civil nor military communication or reconnaissance satellites. In this context, it is reasonable to develop in Poland own independent load-lifting system that will become a factor of progress in the development of the national space technology. As a result, Poland would achieve completely new capabilities in space technology, which until now have been reserved for countries possessing and developing space technologies. The development and analysis of the possibilities of such a system would be a great opportunity for Polish technical universities as well as legal entities and companies that would like to invest their resources in the broadly understood space segment.

Preliminary analysis showed that a modernized MiG-29 aircraft (operated by the Polish Armed Forces) could be used as an aviation platform capable of carrying out a space rocket weighing up to 4000 kg, which would allow taking micro- or nano-satellites into orbit. What is more the second stage of the rocket W-755 from the S-75M anti-aircraft system "Volkhov", in the West known as SA-2C "Guideline", was selected as a space rocket orbiter [10].

The main purpose of this work was to obtain, using CFD methods, a reliable information on aerodynamic properties of a carrier aircraft and a space rocket orbiter assembly. Aerodynamic properties of launch vehicles also affect the vehicle's trajectory. Therefore, it is extremely important to know the reliable aerodynamic characteristics of the airplane - rocket assembly. Moreover, the applied method allows the analysis of the influence of individual elements of the assembly on aircraft aerodynamic properties. In order to acquire these information authors decided to use a ANSYS Fluent software [11] based on solving partial differential equations using the Finite Volumes Method. Various science papers [12, 13, 14, 15] shows the possibilities of using this type of software or performing flight tests to possess an overall information regarding to aerodynamic characteristics of aircraft or its parts. Bearing in mind this fact the article novelty based mainly on using CFD methods to analyze aerodynamic properties of complex geometry airplane carrier with a space rocket orbiter. What is more, in order to confirm the correctness of the chosen method the obtained results have been compared with the results of experimental tests carried out in the wind tunnel. It will also prove that adopted method is sufficient for solving this type of problems.

The following sections of this paper describe the development of aircraft CAD model using Reverse Engineering methods and the process of preparing computational model necessary at the phase of numerical aerodynamic analysis. Section 4 shows quantitative and qualitative results of performed analysis, and the last sections conclude the paper with final remarks.

2. Development of aircraft CAD model using Reverse Engineering methods

To create a CAD model of an existing aircraft there is a need to have a detailed construction documentation. Otherwise, the real object must be digitized. A plane geometry must be transferred to virtual reality using reverse engineering methods. The results of this process is usually the set of points (point cloud) that defines external geometry of an object. Point cloud is used to obtain curves, surfaces and solids that are finally used to create an aircraft numerical model. To accomplish this task the specialized software like ATOS Professional, SIEMENS NX and Geomagic Design X were used. To analyze forces that are acting on an airplane during flight we need to develop an external geometry model. Geometric model is a starting point for developing series of models for numerical and experimental analysis of various phenomena.

During digitization process of MiG-29 outer surface optical scanning system ATOS II Triple Scan was used. This system is based on optical triangulation method. Precise fringe patterns are projected onto the surface of the object and are captured by two cameras based on the stereo camera principle. As the beam paths of both cameras and the projector are known in advance due to calibration, 3D coordinate points from three different ray intersections can be calculated. This triple scan principle offers advantages for measuring reflective surfaces and objects with indentations. The result is complete measuring data without holes or erratic points. The accuracy of optical measuring systems is based on state-of-the-art optoelectronics, precise image processing and mathematic algorithms, ensured by stable precision standards and an automated calibration procedure [16].

Figure 1 - ATOS II Triple Scan and ATOS Compact Scan optical measuring systems.

Measuring system captures up to 5 million measuring points per scan. The accuracy, measurement resolution and measuring area are completely adaptable to the application requirements. This flexibility allows measurement of a large part spectrum with the same sensor head, and when used in combination with TRITOP, the ATOS System is capable of scanning large parts with a high local resolution. Due to size of the measuring object, the photogrammetric measurement using the TRITOP measuring system was made at first.

The process of reproducing the external geometry of an airplane along with the develop of their numerical models is an extremely complex task in the field of reverse engineering. This process is divided into 7 main steps, which are:

1. Aircraft preparing for measurement process.
2. Placing markers on aircraft outside surface.
3. Measuring position of markers.
4. Surface shape measurement.
5. Analysis of measurement results.
6. Completion of missing fragments.
7. Aircraft CAD model development.

During digitization process of MiG-29 aircraft reference points were attached to the surface of the measured object to improve accuracy of measurements made using photogrammetric systems. Reference points coverage density of measured surface depends on its shape and the accessibility of measuring head during measurements. Figure 2 present an example of the measuring field of the ATOS II Triple Scan measuring system illuminated with blue light.

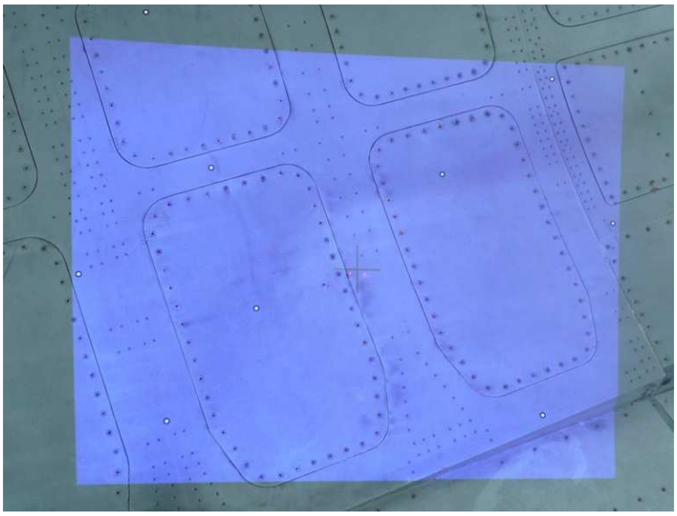


Figure 2 - An example of the measuring field of the ATOS II Triple Scan on the aircraft surface.

Due to size of measuring object, aircraft external surface was divided into several measuring zones. Object geometry obtained using ATOIS II Triple Scan is represented by points clouds that were placed in the appropriate place of the virtual space thanks to previously measured position of non-coded reference points. Figure 3 shows partial measurement results regarding to wing, fuselage and tail section of MiG-29.

Figure 3 - Partial measurement results regarding to wing, fuselage and tail section.

In the next work phase of digitization process a polygonization of points cloud into a grid of triangles was made. In this complex process scanned surface patches were additionally matched to the rest using least squares method. The result of this process is external geometry surface model in triangle grid form. Accuracy of developed model might be checked using aircraft maintenance documentation, for example. The validation of the model was made at the end of polygonization process. The characteristic dimensions of aircraft surface model were determined and compared with data from documentation.

Triangular mesh or points cloud model obtained during digitization process is not a continuous surface model. To create a closed, continuous and smooth surface model you need to generate from the points cloud defined curves that will be used to build surfaces. Information about the object stored in the form of a set of points is poorly legible, therefore it is necessary to develop a method capable of extracting the necessary information from the database with selection of points that are really useful so that the points that meet the filtration criteria can be used for plotting of defining curves for objects to be reproduced.

Process of developing an aircraft surface model with use of definition curves is extremely time consuming. Due to size of model being developed, main construction sections of aircraft were prepared in separate tasks. Created surfaces were repeatedly improved to obtain a satisfactory smoothness.

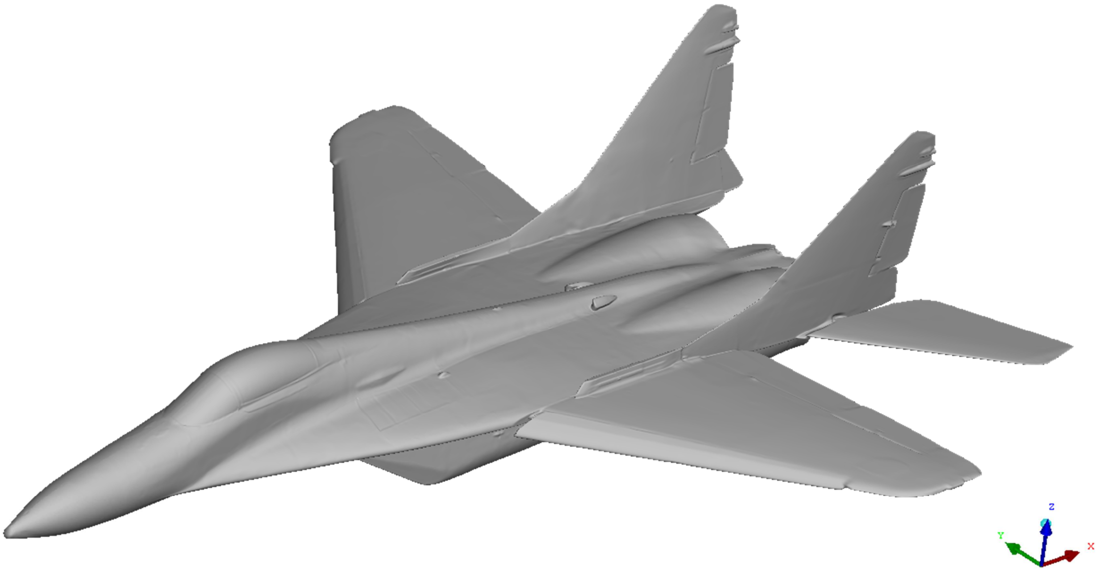


Figure 4 - Complete MiG-29 aircraft CAD model.

3. Development of computational model of a carrier aircraft and a space rocket orbiter assembly

Dynamic development of microprocessor technology and methods of Computational Fluid Dynamics has enabled the simulation of many phenomena occurring during the flow of fluids around solid bodies. CFD is a branch of fluid mechanics focused on detailed analysis and modeling of flows using numerical methods. In the theory of fluid mechanics, movement of liquids and gases is described by a system of differential equations [17]:

- Navier Stokes equation (equation of momentum conservation) in the form:

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p + \nabla(\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F} \tag{1}$$

where:
p - static pressure;
$\rho\vec{g}$ and $\vec{F}$ are, respectively, gravitational forces and external forces, e.g., increasing as a result of flow through a dispersed phase;
$\bar{\bar{\tau}}$ - stress tensor.

$$\bar{\bar{\tau}} = \mu\left[(\nabla\vec{v} + \nabla\vec{v}^T) - \frac{2}{3}\nabla\cdot\vec{v}I\right] \tag{2}$$

where:
μ – kinematic viscosity;

I – unit matrix.

- equation of flow continuity (mass conservation equation in relation to fluid treated as a continuous medium) in the form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \tag{3}$$

where:
S_m - mass source (e.g. as a result of evaporation of the dispersed phase).

- energy conservation equation in the form:

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}\big(u_i(\rho E + p)\big) = \frac{\partial}{\partial x_j}\left[\left(k + \frac{c_p \mu_t}{Pr_t}\right)\frac{\partial T}{\partial x_j} + u_i\left(\tau_{ij}\right)_{eff}\right] + S_h \tag{4}$$

where:
k - thermal conductivity;
E – total energy;
$\left(\tau_{ij}\right)_{eff}$ - shear stress tensor.

$$\left(\tau_{ij}\right)_{eff} = \mu_{eff}\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right) - \frac{2}{3}\mu_{eff}\left(\frac{\partial u_k}{\partial x_k}\delta_{ij}\right) \tag{5}$$

Solving them in the general case is possible only by using numerical methods, e.g. finite volume methods. The above equations are transformed into an integral form:

$$\frac{\partial}{\partial t}\iiint Q dV + \iint F dA = 0 \tag{6}$$

in which Q is used to denote values that are subject to laws of conservation (of mass, momentum, energy) inside a cell, F is a vector of quantities characterizing the stream exchanged with the cell environment, V is the volume of a single control cell, and A is its external surface. Equations written in this way are solved using iterative method (successive approximations). The size of cells in the domain reproducing the air area around the studied geometry is selected so as to accurately reflect the unevenness of the flow field. Unfortunately, this is a very demanding method when it comes to computing resources, both in terms of used memory and computing performance. In the case of geometry of an entire aircraft, calculations are most often made on a computer consisting of several to several dozen parallel working units (nodes), where each analyzes a separate fragment of the computational mesh.

One of the most commonly used packages for solving engineering problems in the field of fluid mechanics and aerodynamics is the ANSYS Fluent software [11] based on solving partial differential equations using the Finite Volumes Method. What is more, to generate the computational meshes ICEM CFD software [18], which is part of the ANSYS package, was used. The ICEM CFD software is an advanced preprocessing tool that allows one to fully prepare a geometric model, i.e. to build or import geometry from a CAD software, as well as to repair and simplify such geometry.

The geometry of the MiG-29 aircraft was developed as a result of the digitization of the outer surface of the aircraft. Furthermore, the geometry of the second stage of the W-755 missile was reproduced on the basis of information found in publicly available literature in this field and photographic documentation.

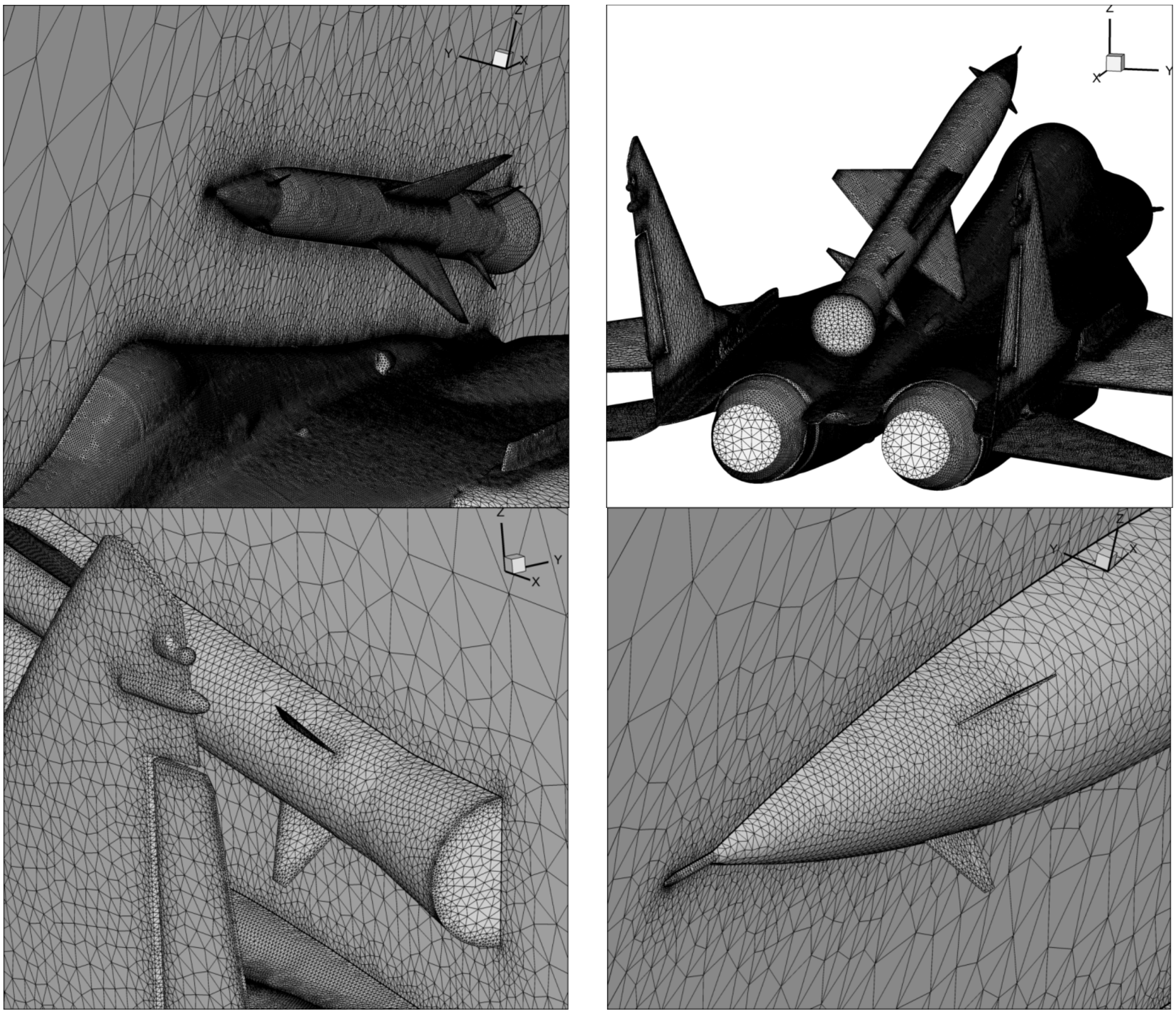


Figure 5 – Computational mesh density on the MiG-29 aircraft in configuration with the W-755 rocket attached.

A non-structural mesh was generated in the area surrounding the aircraft airframe and the W-755 rocket. Five layers of prism cells simulating the boundary layer were generated around the walls of the aircraft and the rocket. 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 [11].

Figure 5 shows the density of the computational mesh generated on the basis of geometric models of the MiG-29 aircraft and the W-755 rocket. Noteworthy is the higher mesh density in areas of the expected high variability of the flow parameters being determined. Such areas include, but are not limited to: leading edges and trailing edges of the wing and control surfaces, areas around engine inlets and outlets, fuselage nose, wing-fuselage connection area and areas of significant surface curvature change.

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 ρ=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 ¼ SCA point on this plane.

Due to the adopted method of presenting results of calculations, the surface of the aircraft and rocket was divided into appropriate zones, which are shown in Figure 6.

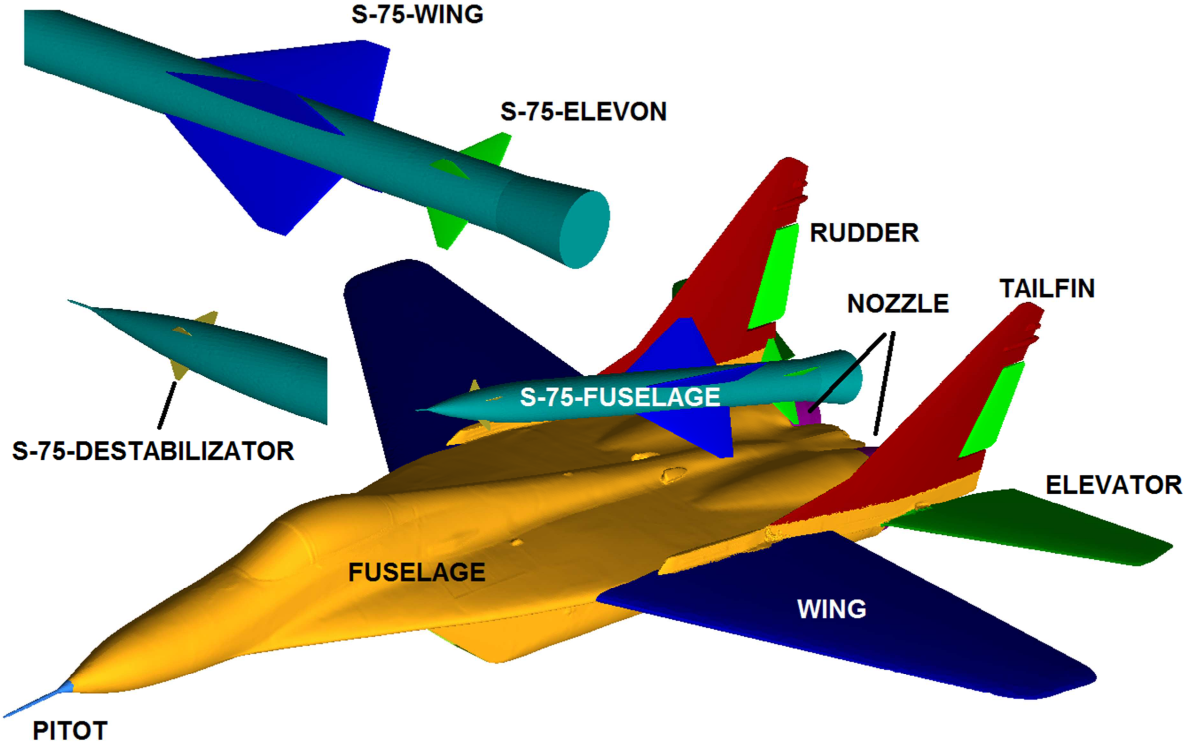


Figure 6 – Division of the aircraft airframe and rocket surfaces into appropriate computational zones.

4. Quantitative and qualitative results of the numerical aerodynamic analysis

During aerodynamic analysis, the right-handed Cartesian coordinate systems were used [19]. 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. The following formulas [20] were used to find the aerodynamic coefficients:

- drag force coefficient

$$C_D = \frac{2 \cdot F_D}{\rho_\infty \cdot v_\infty^2 \cdot S} \tag{7}$$

- lift force coefficient

$$C_L = \frac{2 \cdot F_L}{\rho_\infty \cdot v_\infty^2 \cdot S} \tag{8}$$

- pitching moment coefficient

$$C_m = \frac{2 \cdot M}{\rho_\infty \cdot v_\infty^2 \cdot S \cdot MAC} \tag{9}$$

where:
F_D – drag force [N]; F_L – lift force [N]; M – pitching moment [Nm]; ρ_∞ – air density [kg/m^3];
v_∞ – 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 numerical analysis in the form of aerodynamic characteristics presented as a function of the angle of attack obtained for the MiG-29 aircraft in the configurations without the W-755 rocket (CFD) and with the W-755 rocket (CFD_A+R). The characteristics of the drag coefficient (Fig. 7) clearly show that the greatest impact of the W-755 rocket on increasing the value of the drag coefficient can be observed in the range of the angle of attack α = -12° ÷ 12°. However, this is a relatively small increase. What is more, for angles of attack smaller than α = -28° and larger than α = 38°, the obtained values of the drag coefficient are smaller for the aircraft in the configuration with the W-755 rocket.

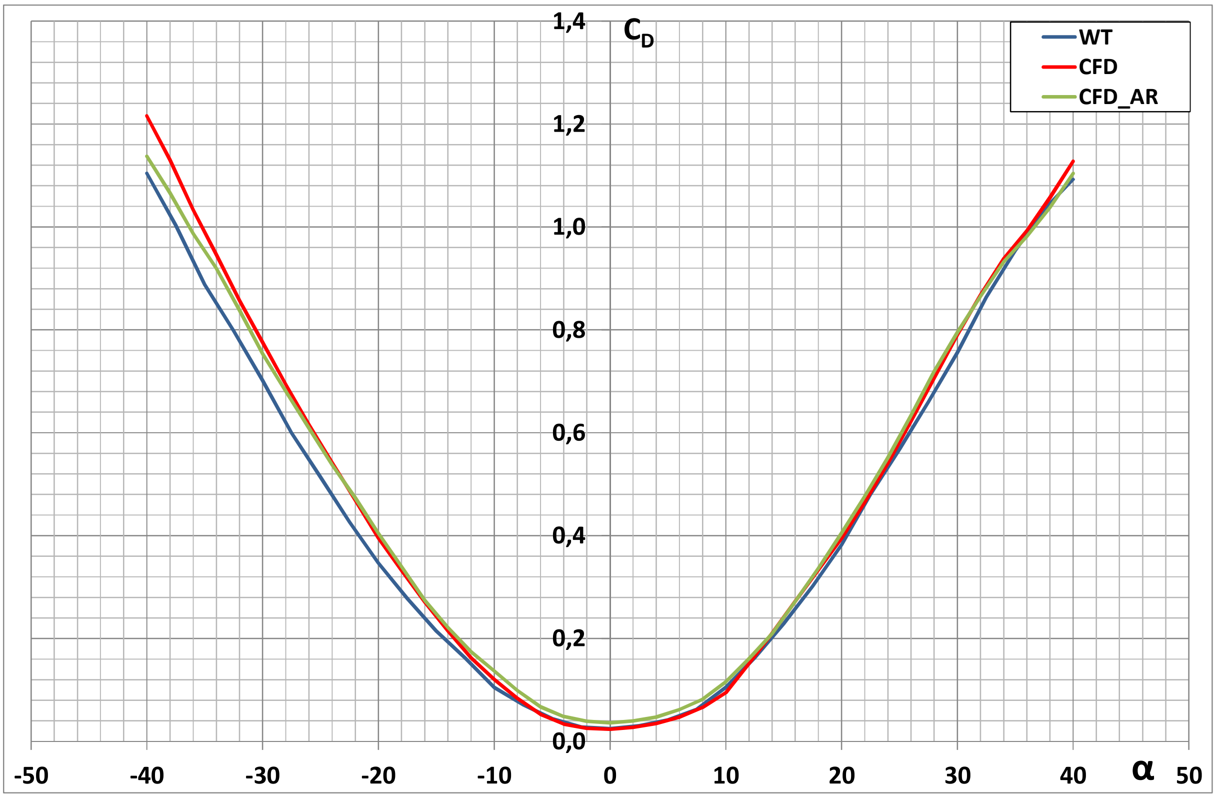


Figure 7 – Comparison of aerodynamic drag characteristics of MiG-29 aircraft with and without the W-755 rocket.

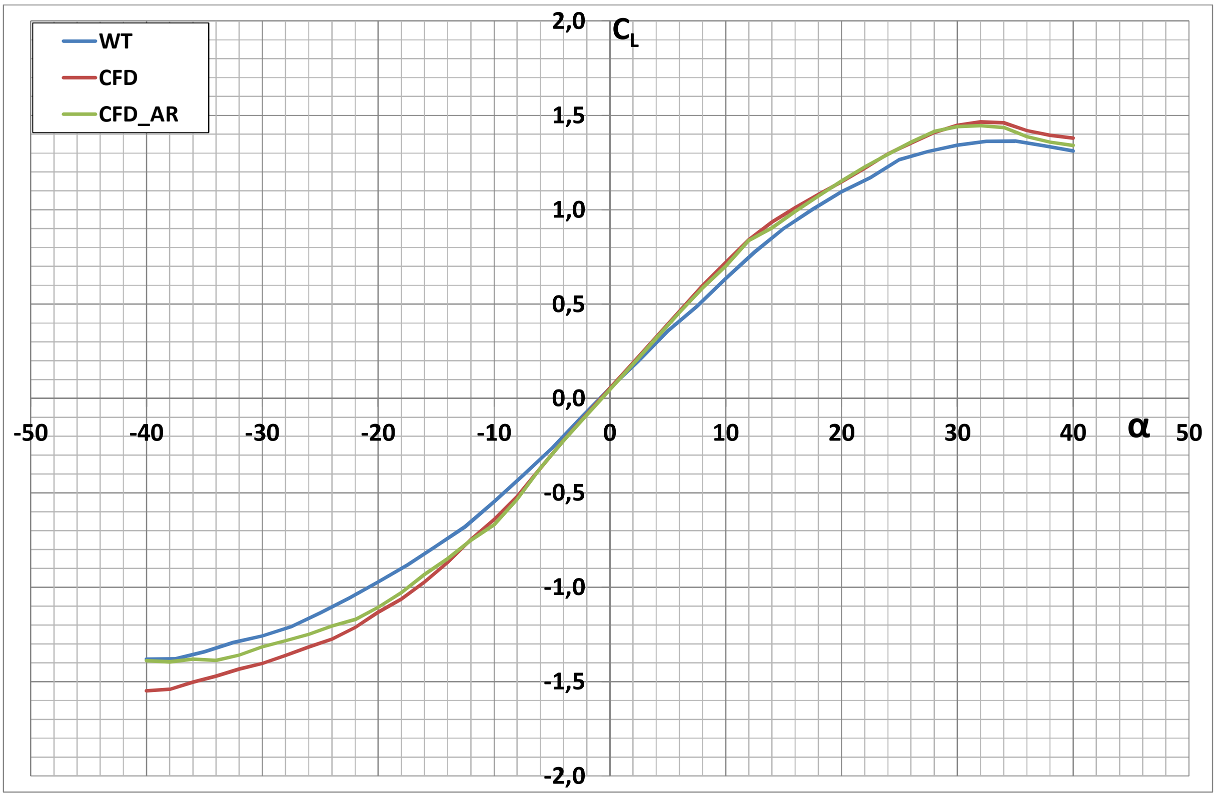


Figure 8 – Comparison of aerodynamic lift characteristics of MiG-29 aircraft with and without the W-755 rocket.

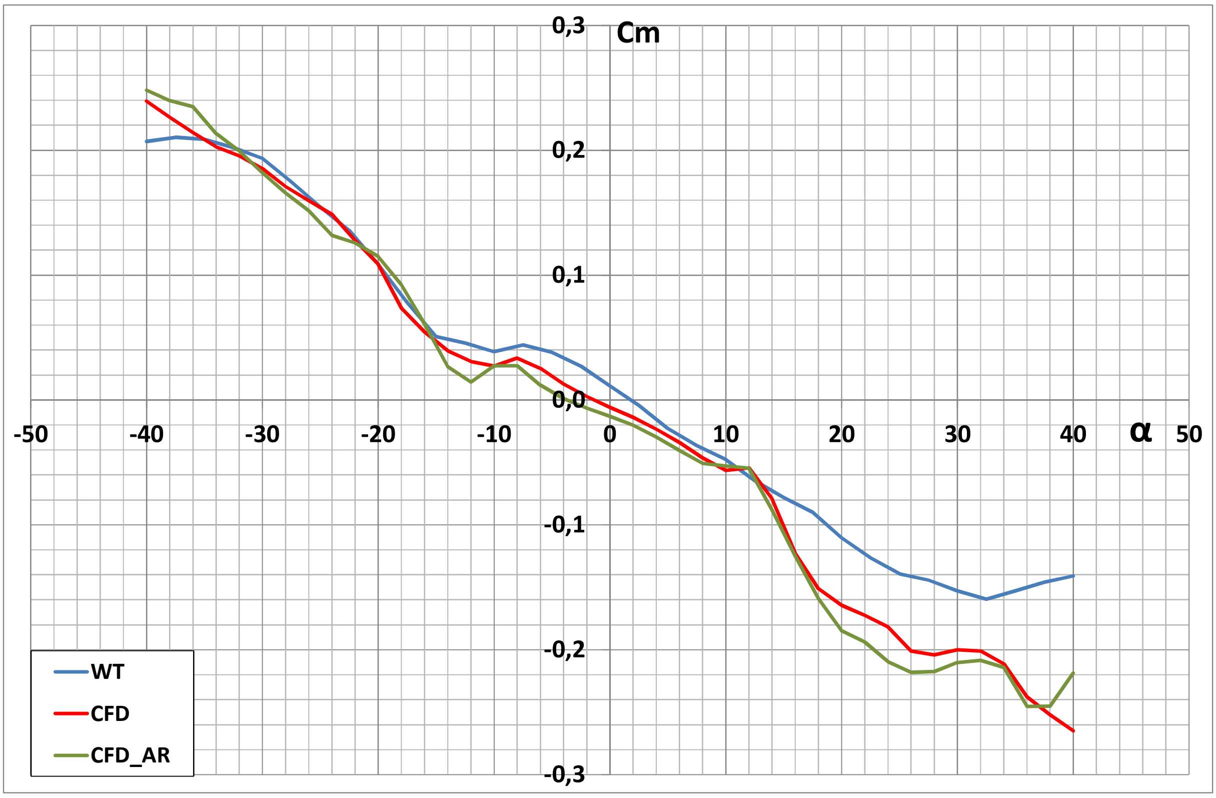


Figure 9 – Comparison of pitching moment characteristics of MiG-29 aircraft with and without the W-755 rocket.

However, on the diagram of the lift coefficient (Fig. 8), it can be seen that for angles of attack in the range α = -20° ÷ 32°, the impact of the W-755 rocket on the change in the lift coefficient is negligibly small. A slight decrease in the absolute value of the lift coefficient was obtained for the angle of attack smaller than α = -20° and greater than α = 32°. Also, on the characteristics of the pitching moment coefficient (Fig. 9), no significant impact of the W-755 rocket on the change in the aircraft stability in the longitudinal channel was observed. The rocket has the strongest impact on the change of the pitching moment coefficient for angles of attack greater than α = 18°. In relation to the adopted pole of the pitching moment, which is in 25% of the SCA, the MiG-29 aircraft in the configurations both without and with the W-755 rocket, is statically stable practically in the entire range of the analyzed angles of attack.

In addition, the results of numerical analysis were compared with the results of experimental tests (WT) carried out in a low-speed wind tunnel of the Institute of Aeronautics of the Faculty of Mechatronics and Aviation of the Military University of Technology [21]. The tests were carried out for the MiG-29 scale model in the configuration without the W-755 rocket. 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 MiG-29 aircraft for the needs of aerodynamic analysis. Possible 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 10 show the impact of components of the MiG-29 aircraft airframe and the W-755 rocket on value of aerodynamic drag coefficient. In the range of angles of attack α = -12° ÷ 12°, the main sources of drag are the wing and the fuselage. The share of the airfoil, fuselage and tailplane in the total value of the drag coefficient increases with the increase of the absolute value of the angle of attack. The presented results confirms the negligible impact of structural assemblies of the W-755 rocket on the drag coefficient of the MiG-29 aircraft. In addition, this is evidence of the correct selection of the location of the rocket relative to the aircraft airframe.

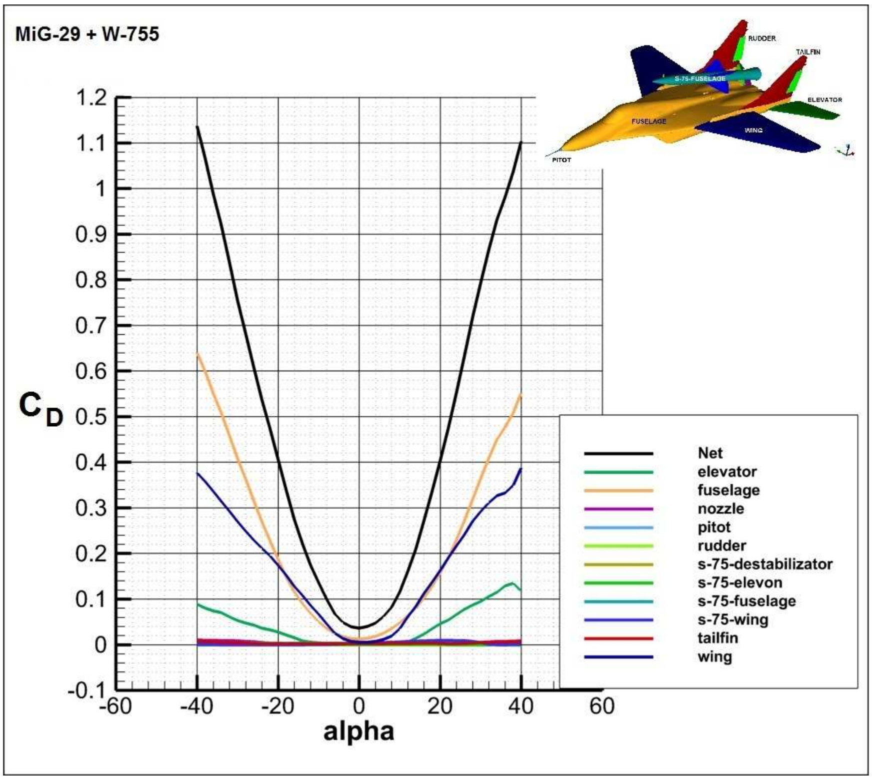
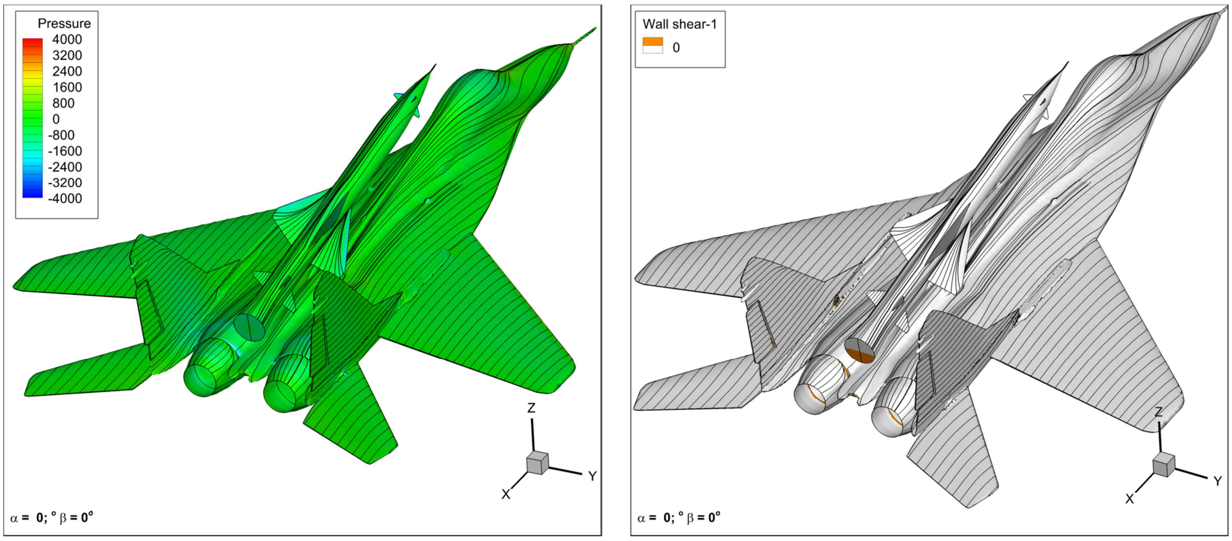
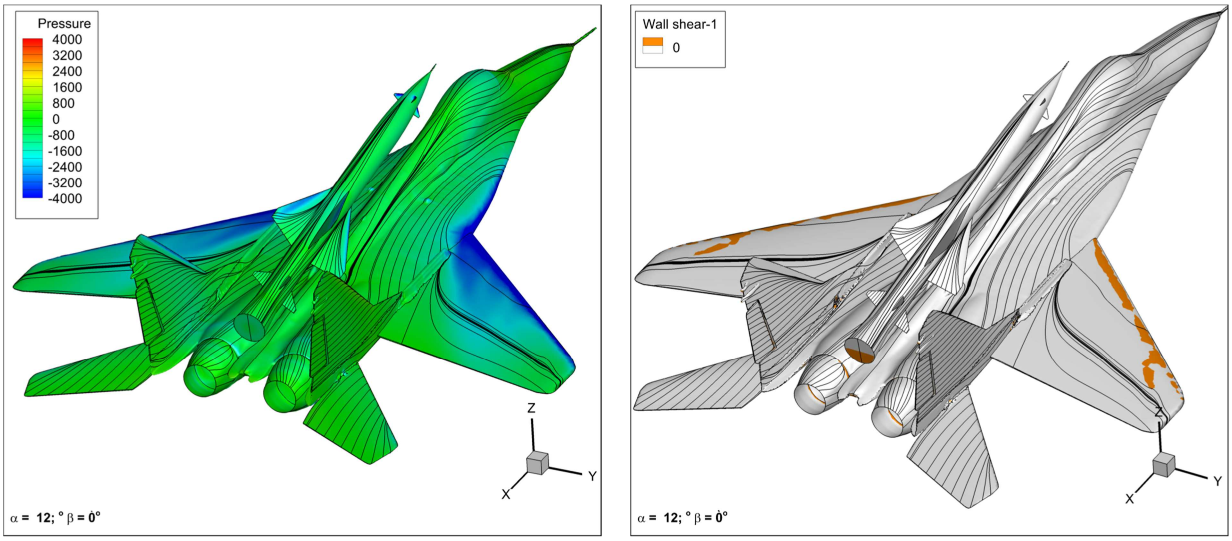


Figure 10 – Components of the aerodynamic drag coefficient as a function of the angle of attack for individual division zones of the geometry of the airframe of the MiG-29 aircraft and the W-755 rocket.

α = 0º



α = 12º



α = 24º

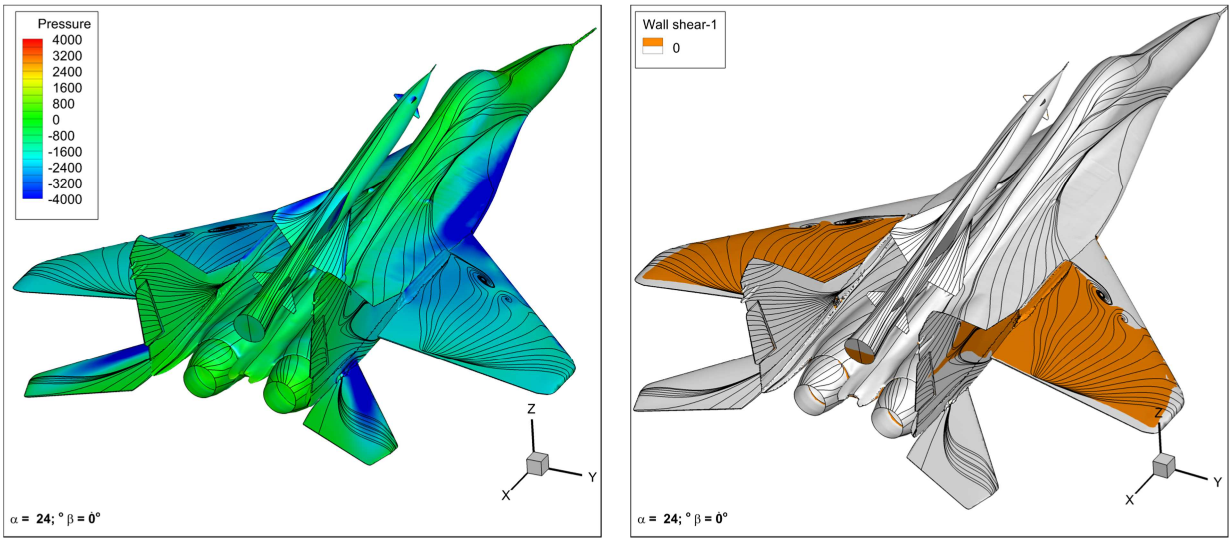


Figure 11 – Visualization of pressure distribution and flow detachment areas with streamlines on the surface of the aircraft in the configuration with the rocket for angle of attack α = 0º, 12º, 24º.

Figure 11 presents a qualitative results obtained for selected angles 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. The formation of such areas indicates flow separation, but one must be careful when drawing conclusions, because areas of reverse flow also arise around windward impact points, which, on lifting surfaces at high angles of attack, can move far to the back of the airfoil.

It can be seen in the presented drawings that as the angle of attack increases, the negative pressure area on the upper surface of the wing increases. For smaller angle 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, air inflow and fuselage surfaces gradually increases. On the other hand, separation of flow begins at the tip of the wing, which is characteristic of a swept wing. As the angle of attack increases, the separation area expands to cover the entire wing. Due to the aerodynamic configuration comprising the lift-generating fuselage, the MiG-29 aircraft obtained a large critical angle of attack $\alpha_{kr} = 34°$. It can be seen that below the critical angle of attack, even if separation has already occurred on the wing, airflow is still attached to the upper surface of the fuselage. After analyzing the direction of the pathlines on the fuselage surface, it should be stated that this is due to the appropriate shape of the fuselage surface and the leading edge extension. In the presented range of angles of attack, no separation was found on the surface of the tailplane.

In the whole range of angles of attack studied, no large value of the stream inflow angle was observed on the W-755 rocket fuselage and its elevons. On the other hand, the wings of the rocket show some relationship between the flow around the structure and the angle of attack.

5. Conclusions and final remarks

In the course of the research work, a number of numerical aerodynamic analyzes of the low cost satellite launch system were carried out. Numerical analysis was performed using the finite volume method, specialized software and a high-performance computing cluster. Both quantitative and qualitative results were obtained. The values of drag and aerodynamic lift as well as pitching moment as a function of the angle of attack for the analyzed configurations of the MiG-29 aircraft were determined. For the selected flight conditions of the aircraft, pressure maps with pathlines on the airframe surface were determined and areas of flow separation, i.e. areas of reverse flow on its surface, were presented. The presence of the carried rocket W-755 does not significantly affect on the flowfield around the MiG-29 aircraft and does not cause any degeneration of vortices generated by the leading edge extension. Influence of the leading edge extension on the aerodynamic characteristics of the MiG-29 was observed. The obtained results will have a significant impact on the decisions of the research team regarding the final shape of the low cost satellite launch system being developed. In addition, the resulting aerodynamic characteristics can be used at the stage of determining loads acting on the structure of the aircraft during the flight and to determine conditions for safe separation of the aircraft and the rocket. High comparability between the results of numerical analyzes and the results of experimental tests indicates the correctness of the adopted research methodology. Finally, it should be noted that the development of Polish, independent and low-cost system for lifting loads into low Earth orbit will become a factor of progress in the development of domestic space technology.

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7. Copyright Statement

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