

Aerodynamic performance of the XGyro fuselage–empennage airframe – a numerical and experimental investigation

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Abstract

This paper presents the results of an aerodynamic investigation of the XGyro fuselage–empennage airframe. The main rotor was not included in the present study in order to isolate the aerodynamic behaviour of the airframe. A combined research methodology was applied, integrating computational fluid dynamics (CFD) simulations with experimental validation in a low-speed wind tunnel. Numerical analyses were performed using ANSYS Fluent with the $k-\omega$ SST turbulence model for a wide range of angles of attack and sideslip angles. Wind tunnel tests were conducted on a 3D-printed scaled model under corresponding flow conditions. The study focused on aerodynamic force and moment coefficients and their dependence on flow angles. The results demonstrate good agreement between numerical and experimental data, particularly for lift and drag characteristics. Both approaches confirmed longitudinal static stability and predictable lateral–directional behaviour of the analysed airframe. The maximum C_Z/C_X ratio was obtained at $\beta = 0^\circ$ and $\alpha = 10^\circ$. The results provide insight into the aerodynamic characteristics of the fuselage–empennage configuration and support further design and development of the overall XGyro concept.

Keywords: aerodynamics, Unmanned Aerial Vehicle (UAV), Computational Fluid Dynamics (CFD), wind tunnel testing, hybrid aircraft

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Highlights

- Hybrid XGyro UAV combining gyroplane and multicopter features was investigated.
- Aerodynamic characteristics were studied using CFD simulations and wind-tunnel experiments.
- CFD predictions showed good agreement with experimental data.
- The configuration demonstrated longitudinal and lateral–directional stability.
- Low drag and high aerodynamic efficiency were observed under cruise conditions.

1. Introduction

An important aspect of research on unmanned aerial vehicles is their operational reliability, which is significantly affected by environmental conditions such as strong winds, high temperatures, and humidity, as demonstrated in [1]. These

factors should be considered already at the preliminary design stage, as they directly influence aerodynamic performance and operational reliability. The aerodynamic properties analyzed in the present study play a direct role in the operational robustness and performance of the unmanned aerial vehicle and, consequently, have a measurable impact on its reliability under actual flight conditions, as they determine the response of the airframe to varying flow conditions such as changes in sideslip angle, which lead to increased aerodynamic drag, reduced lift-to-drag ratio, and modifications of moment characteristics. These effects directly influence disturbance tolerance and define the usable operating envelope of the airframe. Aerodynamic analysis is a fundamental element of aircraft design. Despite significant advances in CFD methods, experimental techniques such as wind tunnel testing remain essential for the validation of numerical results. Study [2]

highlights the fact that wind tunnel experiments play a key role in the validation of CFD computations, while study [3] demonstrates that the development of CFD in aviation has been closely linked to experimental data, particularly for separated flows. In [4], the results of various CFD methods were compared with wind tunnel measurements for helicopters, emphasizing the necessity of simulation verification. CFD methods have been widely applied in the aerodynamic analysis of aircraft, including helicopter fuselages and transport aircraft configurations [5,6].

Numerous studies focus on the aerodynamic modelling of helicopter and gyroplane fuselages. Previous studies have investigated the aerodynamic characteristics of helicopter and gyroplane fuselages, including statistical modelling approaches, stabilizer optimization, and the influence of rotor and wing interactions on stability [7–10]. The fundamentals of helicopter aerodynamics were discussed in detail in [11], whereas study [12] presented the design of the stabilizer of the NH90 helicopter. In study [13], the drag of a helicopter fuselage was modelled using CFD, with the results compared against experimental data, while study [14] presented a method for predicting aerodynamic forces acting on the fuselage. The present study focuses on gyroplane and multirotor configurations. Study [15] presents the history and development of gyroplanes, while study [16] discusses advances in the understanding of gyroplane flight dynamics. A gyroplane (autogyro) is a rotary-wing aircraft in which lift is generated by an unpowered rotor operating in autorotation, while thrust is provided by a separate propulsion system. Unlike helicopters, the rotor is not engine-driven in flight, which results in distinct aerodynamic characteristics and stability properties. The research presented in [17] provides fundamental aerodynamic data on the influence of individual structural components of a gyroplane, such as the engine cowling and horizontal tail, on its performance. The results obtained within this study also made it possible to compile aerodynamic data for use in mathematical models. It was demonstrated that certain components, such as the canopy providing the pilot with protection against atmospheric conditions, under certain conditions, may exert a negative effect.

Multirotor systems offer hovering capability and high maneuverability, and their aerodynamic interactions have been

investigated in several studies [18–20]. The results of these studies show that hybrid configurations combining an autorotating rotor with a multirotor propulsion system can enhance energy efficiency.

Previous studies have investigated the aerodynamic characteristics and stability of gyroplanes under various configurations. Study [21] evaluates the influence of individual components of a selected gyroplane on aerodynamic forces. Another study [22] analyzes the influence of sideslip angle on empennage loading, whereas study [23] investigates the longitudinal static stability of a gyroplane for selected tailplane incidence angles. Among other solutions, for example study [24], presents the aerodynamic concept of an unmanned aerial vehicle in a gyrodyne configuration for monitoring power lines and railway infrastructure. It represents a combination of an airframe and a lifting rotor operating in helicopter mode, supplemented with additional tilt rotors. It characterizes and describes an exemplary mission performed by this research model. However, this work is limited to the conceptual level and does not include a detailed aerodynamic analysis. Studies [25], [26] constitute a significant contribution to the analysis of the aerodynamic characteristics and stability of gyroplanes. The present article extends these analyses by presenting a comprehensive aerodynamic investigation of the latest configuration of the XGyro aircraft, drawing on insights from extensive CFD and wind tunnel studies as well as stability analyses and empennage optimization. As part of the preliminary research, the team led by Czyż conducted a CFD analysis of a gyroplane with a twin-tail configuration [27], in the next stage, followed by aerodynamic measurements of the fuselage of a hybrid aircraft capable of autorotation [28].

The aim of this study is to perform a comprehensive aerodynamic analysis of the fuselage–empennage airframe of a hybrid gyroplane–multirotor UAV configuration. The investigation focuses on the determination of aerodynamic force and moment coefficients of the fuselage and tail assembly across a wide range of angles of attack and sideslip, using a combined CFD and wind tunnel approach. The main outcome of this study is the reduction of design uncertainty through the aerodynamic characterization and validation of an optimized XGyro fuselage–empennage airframe using a combined CFD and wind tunnel approach. Earlier studies focused on

preliminary geometric configurations and revealed significant design limitations, including excessive aerodynamic drag, insufficient empennage effectiveness, and an adverse influence of the forward booms, which also contributed to stability issues. The present study presents an optimized configuration that formed the basis for the construction of the actual XGyro prototype. Although hybrid configurations combining the characteristics of a gyroplane and a multicopter have been considered in previous studies, systematic aerodynamic analyses supported by combined numerical and experimental validation remain relatively limited. The available studies focus primarily on conventional configurations. In this context, the main contribution of this study is the aerodynamic characterization and validation of an optimized XGyro fuselage–empennage airframe using a combined CFD and wind tunnel workflow. This approach reflects a practical engineering workflow, in which numerical simulations are directly supported by experimental validation to assess the aerodynamic behaviour of a design iteration.

2. Computational model and methodology

The subject of the study was a three-dimensional model of a hybrid unmanned aerial vehicle that included all essential components that could influence the results. Accordingly, the model was divided into the following components (assigning their own selections): the fuselage, mast, main rotor gearbox fairing, empennage (separately: upper left stabilizer, lower left stabilizer, upper right stabilizer, lower right stabilizer), nacelles (left rear nacelle, right rear nacelle), booms (left boom, right boom), and wheels (nose wheel, left rear wheel, right rear wheel). The model did not include the main rotor. The solid model was developed using CATIA V5 software. The separation of its individual components made it possible to conduct a detailed analysis not only of the characteristics of the entire object but also of the influence of each component on the aerodynamics of the investigated object. The dimensions of the XGyro model were $1,000 \times 550 \times 520$ mm (length $\times$ width $\times$ height). In order to describe the position of the gyroplane, the authors used a global Cartesian coordinate system consistent with the clockwise convention. The angle of attack α and the sideslip angle β were measured according to the scheme shown in Fig. 1. All aerodynamic moments were referenced to the

origin of the global coordinate system shown in Fig. 1. This point corresponded to the assumed center of gravity (CG) position of the analyzed airframe. The X-axis was directed rearwards, the Y-axis to the right, and the Z-axis upwards. Positive moments M_x , M_y , and M_z were defined according to the right-hand rule. A positive sideslip angle β corresponded to a rightward yaw of the model nose. The same moment reference point and sign convention were used in the CFD calculations and in the wind tunnel data.

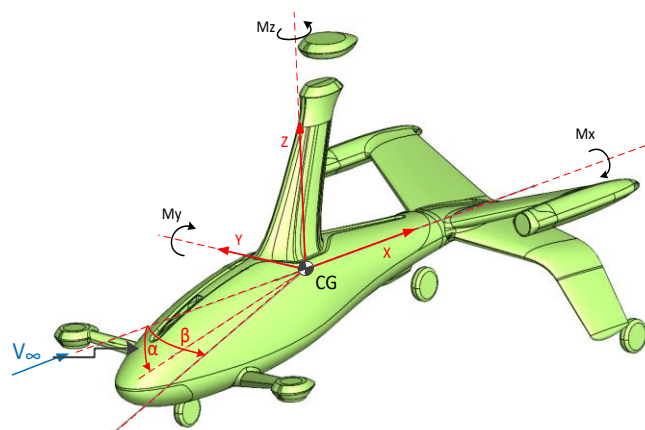


Figure 1. XGyro model with adopted coordinate system: α – angle of attack and β – sideslip angle, CG – assumed centre of gravity and aerodynamic moment reference point.

Numerical simulations of the XGyro model were conducted in the Ansys Fluent environment, which is widely used for the simulation of various physical phenomena [29,30]. The geometry of the investigated unmanned aerial vehicle was prepared in the Design Modeler module by removing discontinuities and sharp edges, as well as performing necessary modifications primarily related to the merging of minor external surfaces, thus reducing the degree of fragmentation of the model. Subsequently, the model was placed within the computational domain with dimensions specified in Fig. 3. Pressure outlet boundary conditions were defined on the outlet surfaces of the domain, while a velocity inlet with a given airflow was applied at the inlet. A symmetry condition was applied to the side surfaces of the domain. The surface of the XGyro, including the stabilizers, empennage, mast, and landing gear, was defined as a wall with a no-slip condition. The analysis assumed free-stream flow, neglecting the ground effect. The calculations were performed using a pressure-based solver in the steady-state configuration. The pressure-velocity coupling was implemented using the SIMPLE algorithm; the partial differential equations

were discretized with second-order spatial accuracy. The convergence criterion was set at residuals of 10^{-5} , along with the stabilization of aerodynamic force values. The $k-\omega$ SST turbulence model was adopted, which effectively captures flow separation in regions with strong pressure gradients. It incorporates both the turbulent kinetic energy and the specific dissipation rate, while limiting the principal stresses within the flow. The turbulence boundary conditions were specified as a turbulence intensity of 1% and a turbulence length scale of 0.28 m. The working fluid was air, modelled as an incompressible ideal gas. A reference temperature of 288 K and a dynamic viscosity of $1.7894 \times 10^{-5} \text{ kg/(m}\cdot\text{s)}$ were assumed. The low Mach number (approximately 0.06 at 20 m/s) justifies the use of the incompressibility assumption.

The computational mesh was generated using the Meshing module. Tetrahedral elements were used with the Curvature Size Function, and a maximum skewness of 0.91. A wall layer was created in the near-wall region (Inflation with Smooth Transition) to ensure accurate resolution of velocity gradients. A grid-independence study was conducted for an earlier representative geometry developed within the same design process. Four computational meshes containing approximately 3.5, 6.5, 8.0, and 12 million elements were analysed under identical boundary conditions and solver settings. The values of the aerodynamic coefficients C_X , C_Z , and C_{MY} were compared. For all three coefficients, the differences between the results obtained using the 6.5-million-element mesh and the finest mesh remained below 1%. Therefore, the mesh containing approximately 6.5 million elements was selected as a compromise between solution accuracy and computational cost. The same meshing strategy, including comparable global and local element sizes and near-wall inflation settings, was retained for the subsequent geometry iterations. Since the introduced modifications were local and did not substantially change the characteristic dimensions of the model or the adopted discretization approach, the same mesh density was also applied to the final geometry investigated in the present study. For the final mesh, the y^+ distribution was evaluated over all surfaces of the investigated airframe. For the representative condition of $\alpha = 0^\circ$, $\beta = 0^\circ$, and $V = 20 \text{ m/s}$, the area-averaged wall y^+ was 10.64, while the local values ranged from 0.15 to 23.09. These values indicate that the near-wall region was not

uniformly resolved within the viscous sublayer over the entire model surface. The possible influence of the intermediate y^+ values on the prediction of wall shear stress and aerodynamic drag is acknowledged as a limitation of the numerical model. Figures 3 and 4 show a global view of the mesh and a detailed view of its portion on selected surfaces. The numerical study focused on determining the aerodynamic forces and moments acting on individual structural components: the fuselage with tail boom, empennage, mast, landing gear, etc. The angle of attack ranged from -25° to $+25^\circ$ in 5° increments, while the sideslip angle was analyzed from 0° to $+25^\circ$, also in 5° increments. All calculations were performed on the aircraft geometry including the above-mentioned components, allowing for the consideration of mutual interactions between them. Aerodynamic results were recorded separately for each of the surfaces indicated in Fig. 2. A general description of the investigated object is provided in studies [28,31].

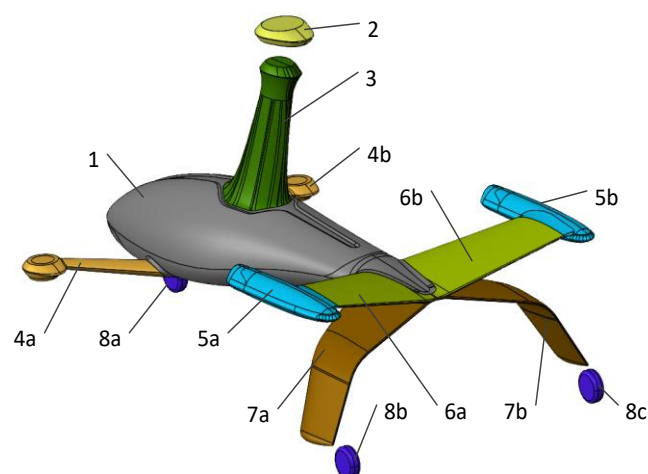


Figure 2. XGyro model with highlighted fuselage (1), head cover (2), mast (3), arms (4a, 4b), engine nacelles (5a, 5b), upper stabilizers (6a, 6b), lower stabilizers (7a, 7b), wheels (8a, 8b, 8c).

The accuracy of the CFD results is influenced by the adopted numerical setup, particularly the mesh resolution and the turbulence model. The $k-\omega$ SST model is widely recognized as suitable for external aerodynamic applications; however, like all turbulence models, it may exhibit limitations in capturing complex separated flow features. In addition, the discretization of the computational domain may affect the prediction of local pressure gradients. These aspects are known to have a more pronounced influence on moment coefficients than on force coefficients, due to their higher sensitivity to the distribution of

aerodynamic forces relative to the reference point.

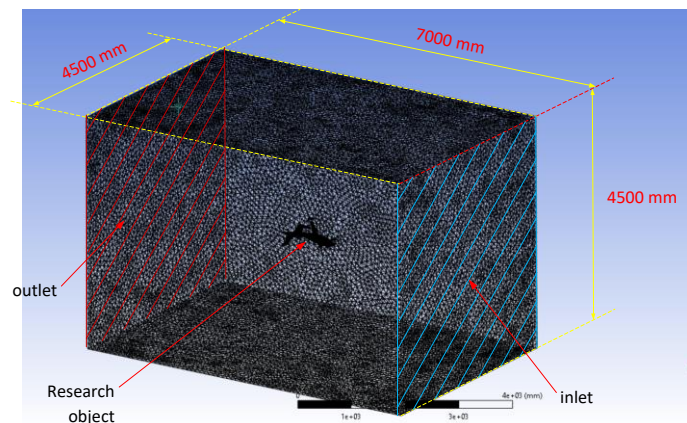
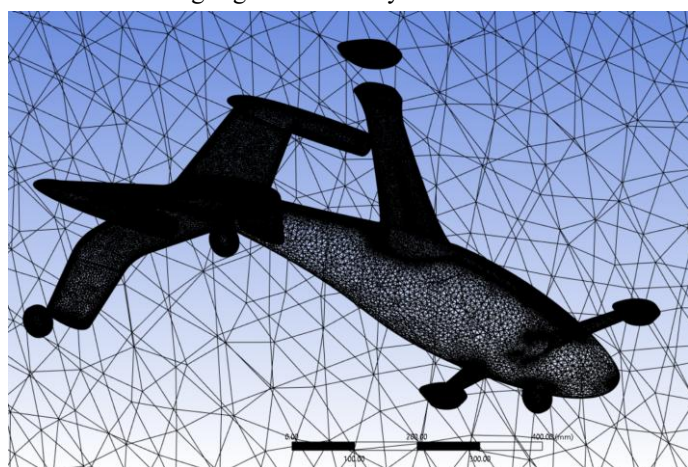
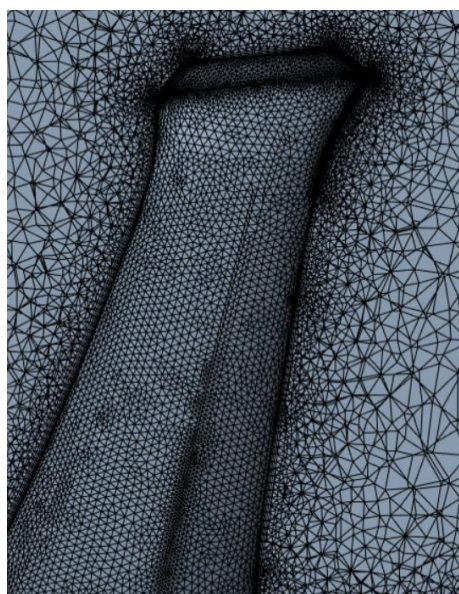


Figure 3. General view of the computational grid and highlighted boundary conditions.



(a)



(b)

Figure 4. Computational grid on the surface of the research object: (a) general view of the complete object including the tail unit, mast and landing-gear; (b) view around the mast.

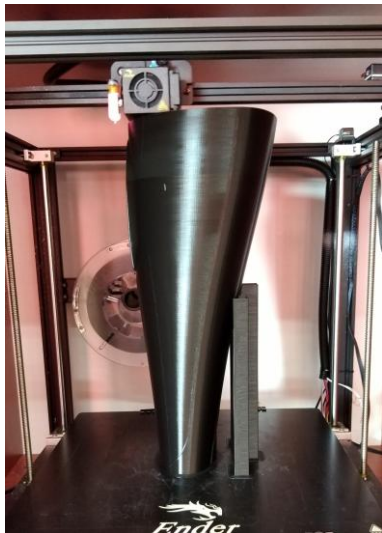
3. Research object and test stand

Based on the developed three-dimensional model of the XGyro unmanned aerial vehicle, a physical model intended for wind tunnel testing was constructed. Fused Deposition Modelling (FDM) additive manufacturing technology was used in its fabrication, enabling the rapid and cost-effective reproduction of complex aerodynamic shapes. The manufacturing process was carried out using a Creality Ender-5 Plus 3D printer, equipped with a build volume that allows for the fabrication of larger components without the need to divide them into multiple segments. The construction material was polylactic acid (PLA), as it is commonly employed in FDM technology due to its ease of processing, sufficient stiffness, and dimensional stability, which is essential for accurately reproducing aerodynamic geometry [32,33].

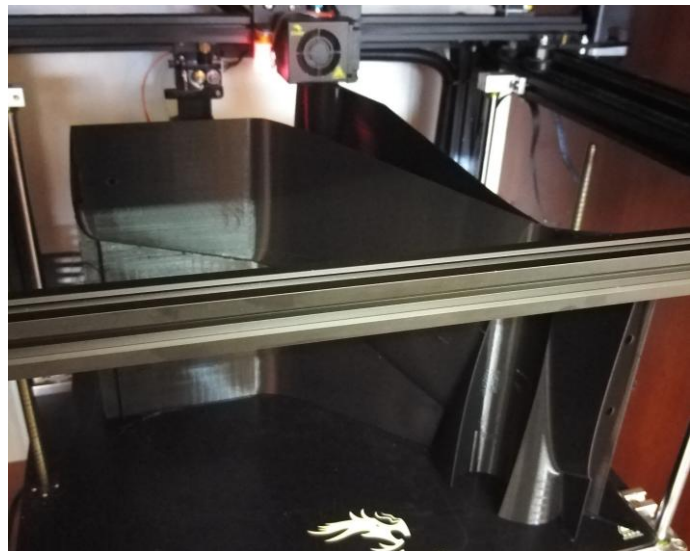
Due to the surface quality requirements, which have a significant impact on the flow characteristics in the wind tunnel, the printed components underwent a finishing process. This process involved the removal of irregularities and layer deposition marks through sanding, as well as filling the joints between segments. Subsequently, the model was coated with paint, which provided a uniform smooth surface that minimized the risk of local flow disturbances and improved the mechanical strength of the model during testing.

The adopted manufacturing technology made it possible to achieve the required geometric accuracy while maintaining low costs and a short production time. Combined with the ability to easily modify geometric elements, this approach proved particularly advantageous in iterative studies requiring verification of multiple design variants. Fig. 5 shows views of selected components of the XGyro model during the printing process.

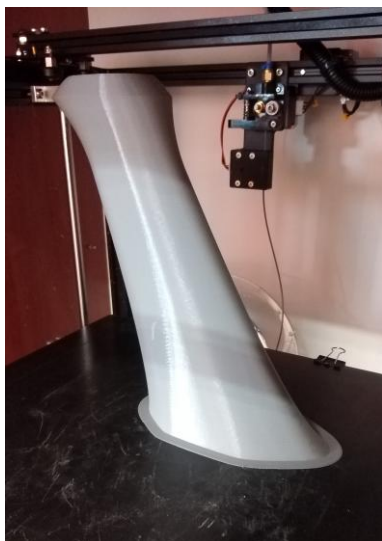
Fig. 6 shows the assembled components of the test object after the surface preparation stage but prior to final bonding. The final object, prepared for testing and mounted in the measurement section of the wind tunnel, has been shown in Fig. 7.



(a)



(d)



(b)



(e)

Figure 5. Selected components of the model during printing:
(a) rear section of the fuselage, (b) mast, (c) left engine mounting boom, (d) main part of the empennage, (e) main rotor hub.



(c)



Figure 6. Components of the test object prior to bonding and painting.



Figure 7. Research object mounted on a mast with a force balance in the wind tunnel.

The experiments were conducted in a subsonic closed-loop wind tunnel located at the Centre for Innovation and Advanced Technologies of Lublin University of Technology. The view of the wind tunnel is shown in Fig. 8, while the view of the test stand and research object in the test section is shown in Fig. 7. The tunnel is horizontally oriented and equipped with two interchangeable test sections: a large environmental chamber with dimensions of $1,800 \times 2,000$ mm and a smaller aeronautical test chamber measuring $1,415 \times 1,275$ mm [34]. The authors used a smaller test chamber for the need of the present study. The tunnel is powered by a single axial fan with a diameter of 2,400 mm, driven by a 160 kW electric motor. This setup enables air flow velocities of up to 60 m/s, with a turbulence intensity below 0.3%. The entire installation has external dimensions of approximately $18.7 \times 7.4 \times 3.3$ m (3.7 m including reinforcements). The model was mounted on

a monolithic six-component aerodynamic balance FMT 625-1b, installed in the test chamber on a rotary platform with a mast, which enabled precise adjustment of the angle of attack α and the sideslip angle β (see Fig. 9). At $\alpha = 0^\circ$ and $\beta = 0^\circ$, the projected frontal area of the model was 0.068 m^2 , corresponding to a geometric blockage ratio of approximately 3.77% relative to the 1.804 m^2 test-section area. However, no wind-tunnel blockage correction or external model-support interference correction was applied to the experimental results.

The balance was connected to a QuantumX MX840B signal amplifier from HBM, and the measured forces and moments were transformed from the balance system to the flow system. Each time the measurement system was powered on, a waiting period of 20 - 30 min was observed prior to testing to allow all components of the measurement system to warm up and stabilize the readings. The transducer was factory-calibrated at the calibration facility of the Maritime Advanced Research Centre (CTO S.A.) The measurements were carried out using a dedicated setup with appropriate libraries for the LabVIEW environment and measurement scripts. The measurement range for forces and moments was as follows: $F_X = \pm 205 \text{ N}$, $F_Y = \pm 240 \text{ N}$, $F_Z = \pm 620 \text{ N}$, $M_X = \pm 37.5 \text{ Nm}$, $M_Y = \pm 27 \text{ Nm}$, $M_Z = \pm 21 \text{ Nm}$. The calibration matrix was determined on the basis of 624 calibration points. According to the factory test protocol, the standard calibration errors were 0.141% for F_X , 0.199% for F_Y , 0.102% for F_Z , 0.061% for M_X , 0.102% for M_Y , and 0.091% for M_Z . The corresponding mean errors were 0.107%, 0.147%, 0.078%, 0.039%, 0.071%, and 0.066%, respectively. The flow velocity was measured using a Prandtl tube operating within the range of 3-100 m/s, while the signal was processed by an Aplisens APR-2000G pressure transducer. Additionally, differential pressure sensors (0-2.5 kPa), temperature sensors (-20 to 80 °C), humidity sensors (0-100% RH), and velocity sensors (0-70 m/s) were installed, enabling continuous monitoring of flow conditions in the tunnel. For each configuration of the angle of attack and sideslip angle, the signals were recorded for 5 seconds at a sampling frequency of 25 Hz. The measurement was repeated in three series, and the mean value from the three series was used to determine the aerodynamic coefficients presented in this study. The model was attached to balance sting, using a conical threaded joint, which ensured stability during the tests.

The test programme included variations of the angle of attack in the range from -20° to $+20^\circ$ and the sideslip angle from 0° to 20° (in 5° increments). The tests were conducted at flow velocities of 5, 10, 15, and 20 m/s; the main body of this article presents the results for the cruise velocity of 20 m/s.



Figure 8. View of the wind tunnel used for research.



Figure 9. Six-component force balance FMT 625 - 1b.

4. Results and discussion

4.1. CFD simulation results

4.1.1. Pressure and velocity distribution results

The analysis of the pressure distribution on the surface of the aircraft is a key element in assessing its aerodynamic properties, since pressure determines the magnitude and direction of the forces and moments acting on individual structural components. The pressure difference between the upper and lower wing surfaces is responsible for generating lift, whereas local regions of high and low pressure on the fuselage, empennage, and auxiliary components contribute to drag as well as to the pitching, rolling, and yawing moments. This is particularly important in the case of complex hybrid configurations, where interactions between different lifting surfaces may lead to nonlinear aerodynamic effects. Accurate identification of regions with extreme pressure values does not only enable the prediction of aircraft behaviour over a wide range of angles of attack and sideslip but also allows for the optimization of component shape and configuration to improve stability, control effectiveness and energy efficiency. Figures 10–12 present selected pressure contours on the surface of the investigated object, as well as pressure contours in the symmetry plane of

the surrounding flow field, for selected angles of attack α equal to -25° , 0° , and $+25^\circ$, with the sideslip angle $\beta = 0^\circ$. The analysis of the pressure contours for $\beta = 0^\circ$ clearly indicates that variations in the angle of attack significantly affect the extreme pressure values on the fuselage surface. The maximum pressure shows only a slight variation. For all analyzed cases (within the assumed range of angles), this value remains within a narrow range of approximately 223–235 Pa. This is due to the presence of a stagnation point near the fuselage nose and the engine nacelles, where the flow velocity approaches zero and the pressure rises to a level close to the dynamic pressure ($q = \frac{1}{2}\rho v^2$), largely independent of the angle of attack α . For the investigated velocity of 20 m/s and air density of 1.2 kg/m^3 , the dynamic pressure was $q = 240 \text{ Pa}$, which is consistent with the obtained results (e.g., 235 Pa for $\alpha = 0^\circ$).

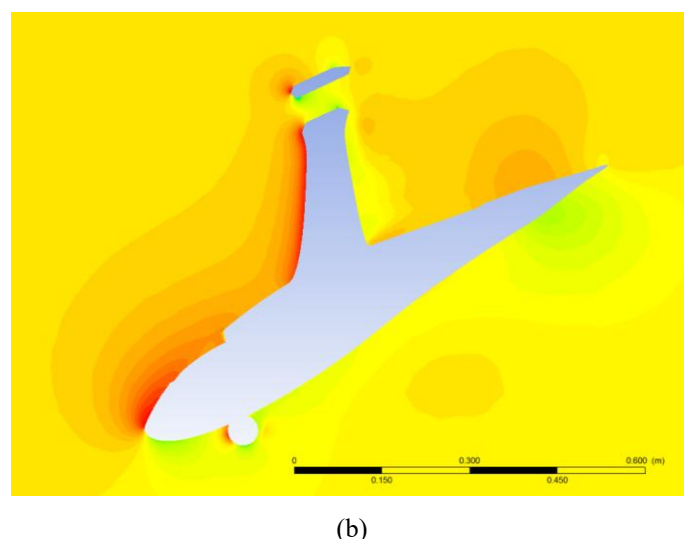
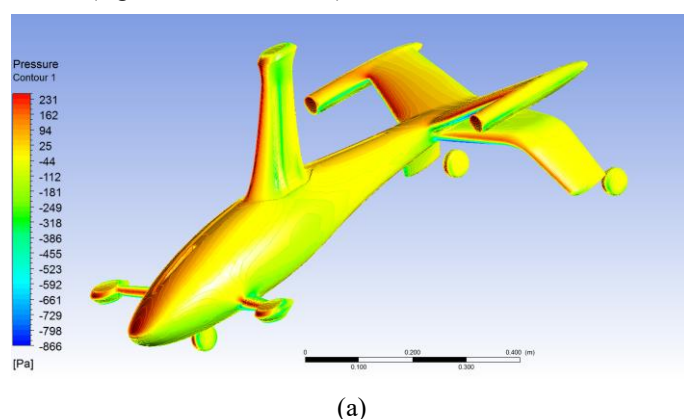
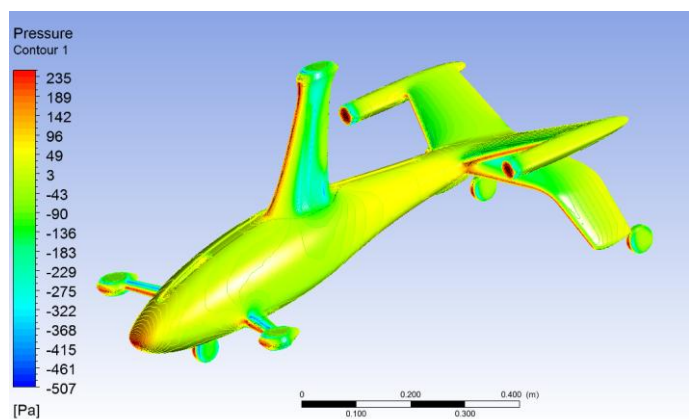
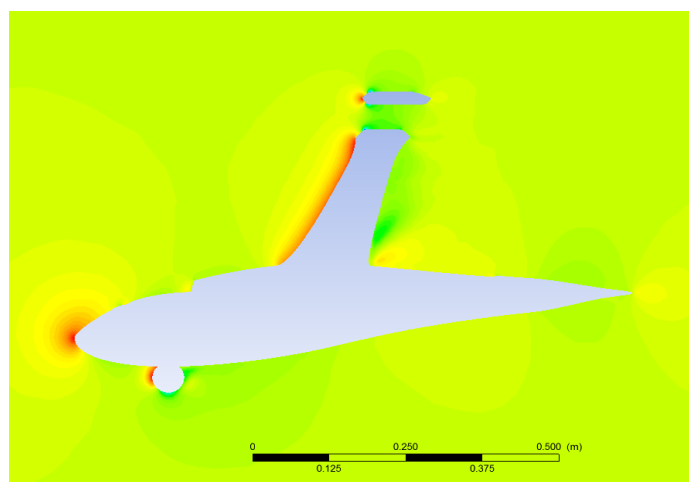


Figure 10. Pressure contour on the surface of the examined object - perspective view (a) and pressure contour in the symmetry plane of the investigated object (b) for $\alpha = -25^\circ$ and $\beta = 0^\circ$.



(a)

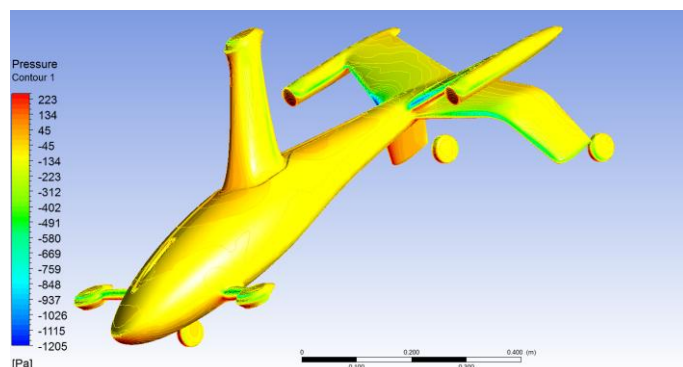


(b)

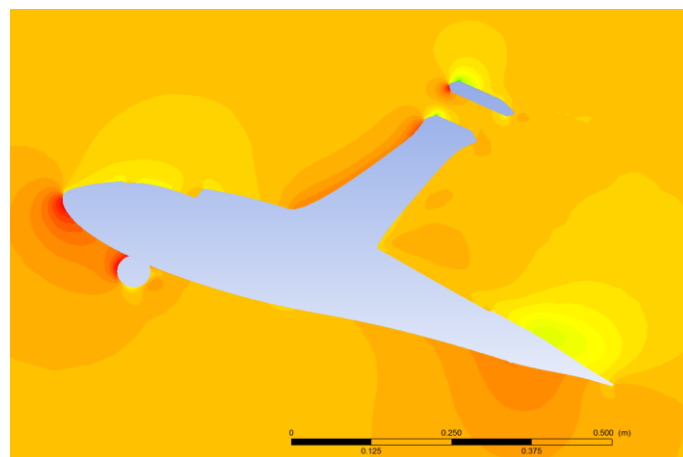
Figure 11. Pressure contour on the surface of the examined object - perspective view (a) and pressure contour in the symmetry plane of the investigated object (b) for $\alpha = 0^\circ$ and $\beta = 0^\circ$.

The minimum pressure (underpressure), on the other hand, exhibits a clear dependence on the angle of attack. With an increasing positive angle of attack, the minimum pressure values successively decrease (become more negative): for $\alpha = 0^\circ$ approximately -507 Pa, for $\alpha = 15^\circ$ about -880 Pa, and for $\alpha = 25^\circ$ as low as -1205 Pa. This is a consequence of the increasing flow velocity over the upper surface of the fuselage and the lifting surfaces of the empennage at higher angles of attack, which generates greater underpressure and intensifies flow separation phenomena. A slight decrease in stagnation pressure is also observed with increasing α (e.g., from 235 Pa at $\alpha = 0^\circ$ to 223 Pa at $\alpha = 25^\circ$), which indicates a shift of the stagnation point and increased pressure losses. For negative angles of attack, a monotonic increase in the minimum underpressure is observed - from approximately -866 Pa ($\alpha = -25^\circ$) through

approximately -763 Pa ($\alpha = -20^\circ$) to -530 Pa ($\alpha = -5^\circ$). This indicates that as the negative angle of attack decreases (approaching $\alpha = 0^\circ$), the underpressure on the fuselage surface systematically weakens. This phenomenon is associated with the decreasing flow angle over the upper surface of the fuselage and the reduction of separation effects.



(a)



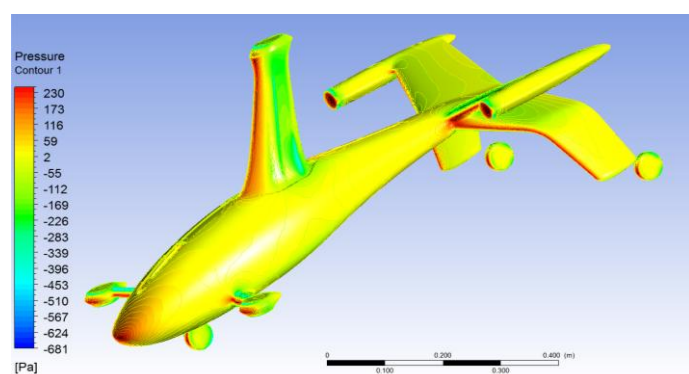
(b)

Figure 12. Pressure contour on the surface of the examined object - perspective view (a) and pressure contour (b) in the symmetry plane of the investigated object for $\alpha = 25^\circ$ and $\beta = 0^\circ$.

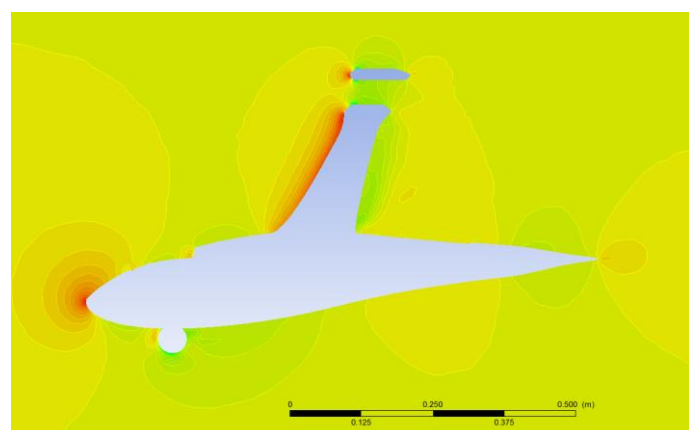
The observed aerodynamic behaviour is primarily governed by several key regions of the configuration, including the fuselage side surfaces, the mast/head-cover region, the fuselage-empennage junction, and the empennage. In summary, the angle of attack has a significant influence on the extreme pressure values. Positive angles of attack lead to a gradual increase in underpressure (more negative minima) and a slight decrease in stagnation pressure, while for negative angles of attack the changes are less regular. However, a tendency toward greater underpressure values at larger negative α is also observed. This indicates that as the magnitude of α increases,

the pressure differences on the object grow, which translates into higher lift and drag forces.

To illustrate the influence of sideslip, selected flow field visualizations for nonzero sideslip angles are presented in Fig. 13 and Fig. 14. The results correspond to $\alpha = 0^\circ$ and $\beta = 10^\circ$ and 20° , respectively, highlighting the development of flow asymmetry around the fuselage. For $\beta = 10^\circ$, the onset of asymmetric pressure distribution is observed, particularly in the region of the vertical tail and lateral components. For $\beta = 20^\circ$, the asymmetry becomes significantly more pronounced, with stronger pressure gradients and extended regions of disturbed flow.



(a)

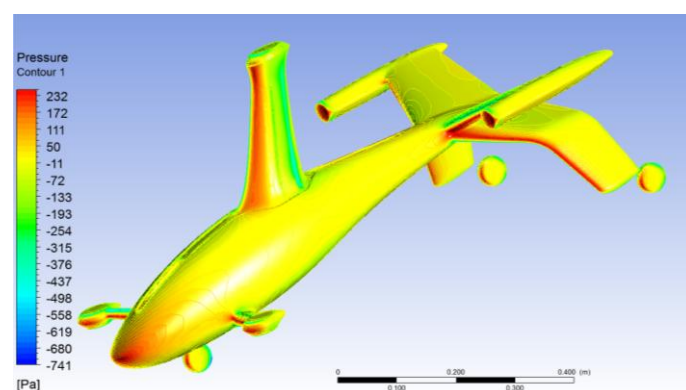


(b)

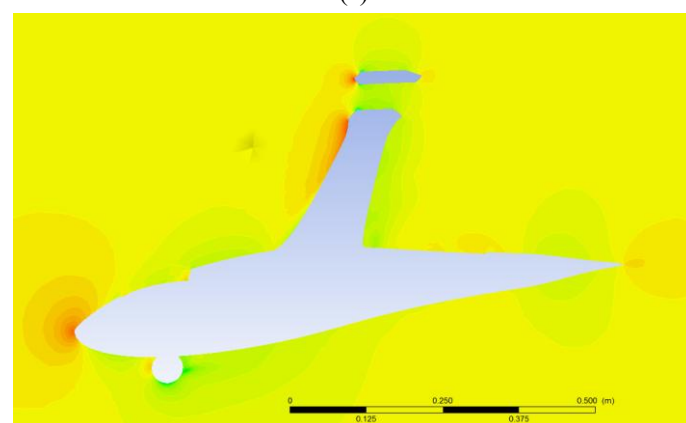
Figure 13. Pressure contour on the surface of the examined object - perspective view (a) and pressure contour in the symmetry plane of the investigated object (b) for $\alpha = 0^\circ$ and $\beta = 10^\circ$.

The analysis of the pressure contours showed that the maximum (stagnation) pressure values remain practically constant throughout the investigated range of the angles of attack ($-25^\circ \leq \alpha \leq 25^\circ$) and sideslip ($0^\circ \leq \beta \leq 25^\circ$), fluctuating around 225-235 Pa, which corresponds to the dynamic pressure

at the cruise velocity. This means that variations in the sideslip angle do not lead to a significant increase in positive pressure values. In contrast, the minimum pressure values show a clear dependence on both the angle of attack and the sideslip angle. With increasing α , the intensity of underpressure on the upper surface of the object increases, reaching values of approximately 1,200 Pa for large positive angles. An increase in β causes a further intensification of underpressure up to $\beta \approx 10-15^\circ$, whereas at $\beta = 20-25^\circ$ a saturation effect or a slight weakening of the extrema is observed, associated with the onset of flow separation. Overall, the key effect of increasing β does not mean an increase in overpressure but rather a deepening of suction regions and an intensification of pressure distribution asymmetry, which results in increased lateral forces and moments as well as a higher risk of flow separation, particularly in the aft fuselage region and near the fuselage-empennage junction.



(a)



(b)

Figure 14. Pressure contour on the surface of the examined object - perspective view (a) and pressure contour in the symmetry plane of the investigated object (b) for $\alpha = 0^\circ$ and $\beta = 20^\circ$.

The analysis of the velocity field around the investigated aircraft provides a valuable complement to the pressure distribution studies, as it allows for a better understanding of the mechanisms responsible for the generation of aerodynamic forces and moments. According to Bernoulli's equation, local flow accelerations are directly associated with decreases in static pressure. Therefore, examination of the velocity fields enables verification and interpretation of the previously identified regions of overpressure and underpressure. Velocity maps also facilitate the identification of regions of flow acceleration, separation, and recirculation, which may contribute to additional drag or unstable moments. In the case of complex hybrid configurations, where numerous interactions occur between the fuselage, wings, and lifting components, velocity field analysis enables the assessment of flow quality in critical regions such as wing roots, pylon areas, and the empennage. This makes it possible to identify sources of energy losses, locate regions requiring geometric modifications, and to gain a better understanding of the relationships between object geometry, pressure distribution, and the resulting aerodynamic forces as well as moments. Taking the above into account, the velocity distribution was examined for the conducted range of simulations. The aerodynamic wake was analyzed with a particular attention to the range of influence of the individual components of the investigated object. Figures 15–17 show the velocity contours in the symmetry plane of the investigated object for a sideslip angle of $\beta = 0^\circ$ and selected extreme angles of attack α equal to -25° , 0° , and 25° , respectively.

Regarding the influence of the angle of attack α at a constant sideslip angle β , it was observed that at small sideslip angles ($\beta \approx 0^\circ$) an increase in the angle of attack α leads to an increase in the maximum flow velocity (flow acceleration effect). In contrast, at higher sideslip angles β (15 – 25°), the opposite trend can be observed: large values of α lead to a reduction in maximum velocity, indicating earlier flow separation and less effective flow acceleration. Increasing the sideslip angle β at a constant angle of attack α leads to higher local flow velocities for small and negative α angles. The opposite trend is observed at large α angles. An increase in β causes a reduction in the maximum velocity values. The highest maximum velocities (42–44 m/s) occur for negative angles of attack (-25° and -20°) at $\beta = 5$ – 10° . For large positive angles of attack (20 – 25°), the

maximum values are the highest at $\beta \approx 0^\circ$ and then decrease with an increasing sideslip angle. These results confirm that the interaction between the angle of attack and the sideslip angle significantly modifies the flow characteristics, particularly in terms of separation and local flow acceleration around the empennage and fuselage.

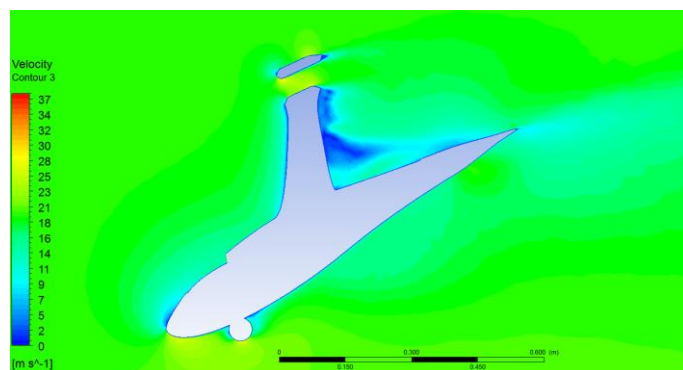


Figure 15. Velocity contour in the symmetry plane of the investigated object for $\alpha = -25^\circ$ and $\beta = 0^\circ$.

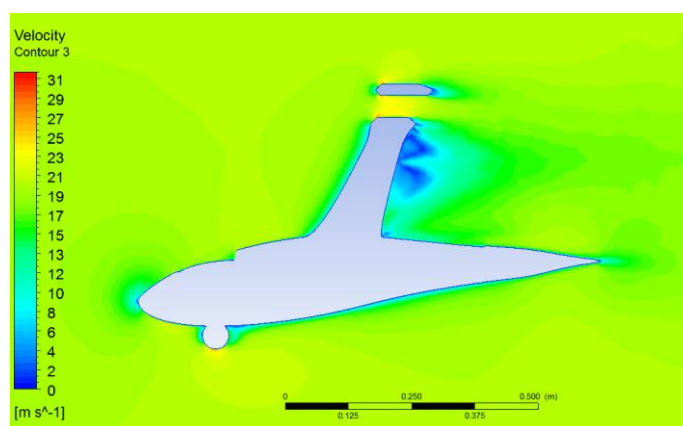


Figure 16. Velocity contour in the symmetry plane of the investigated object for $\alpha = 0^\circ$ and $\beta = 0^\circ$.

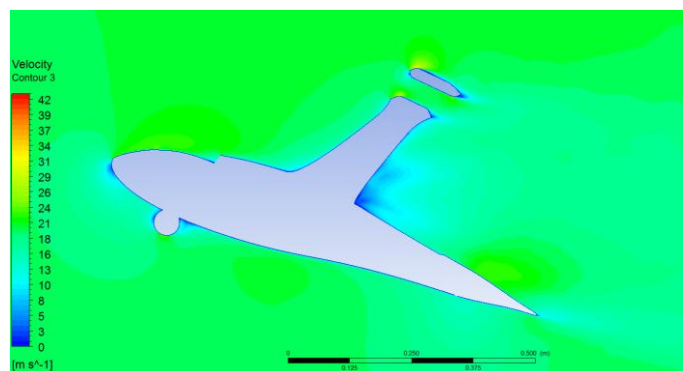


Figure 17. Velocity contour in the symmetry plane of the investigated object for $\alpha = 25^\circ$ and $\beta = 0^\circ$.

Additionally, a velocity contour for $\beta = 10^\circ$ and 20° is presented to illustrate the development of the wake and flow separation under strong sideslip conditions (Fig. 18 and Fig. 19).

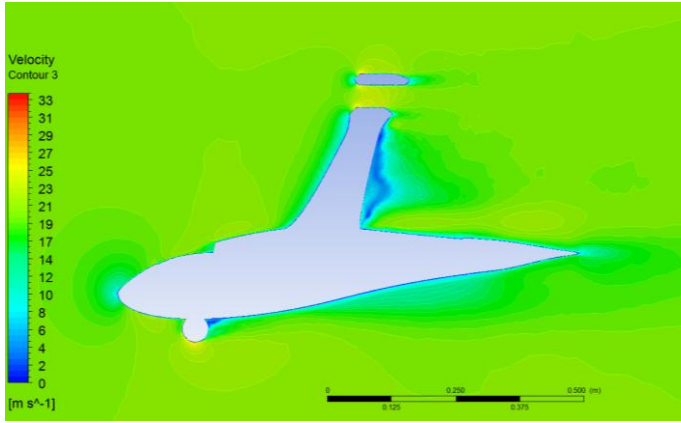


Figure 18. Velocity contour in the symmetry plane of the investigated object for $\alpha = 0^\circ$ and $\beta = 10^\circ$.

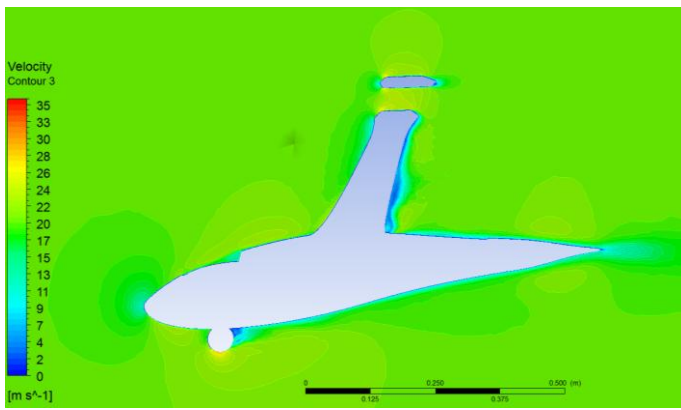


Figure 19. Velocity contour in the symmetry plane of the investigated object for $\alpha = 0^\circ$ and $\beta = 20^\circ$.

The CFD velocity-field results indicate that the aerodynamic shape of the XGyro fuselage is acceptable within the considered range of operational angles of attack and sideslip. Along the main body, the flow remains continuous, with no observed extensive regions of flow separation. Local accelerations along the upper fuselage and in the fuselage-empennage junction region are mild in nature and do not develop into global flow separation. The pressure recovery in the tail section proceeds smoothly (flow contraction without separation), minimizing regions of reduced pressure and reducing the pressure drag component. The regions of reduced velocity visible in the wake of the rotor mast and in the wheel trails are local and narrow. They concern secondary elements in terms of total drag contribution and, considering their structural and operational function, fall within the acceptable design compromise. An analogous verification was carried out for the empennage. The flow approaching the stabilizers remains well organized, and the components located ahead of the empennage do not generate an adverse influence strong enough to interfere with their proper

aerodynamic performance. The degree of flow asymmetry increases with increasing sideslip angle. Overall, the obtained flow pattern supports the design assumptions.

4.1.2. Analysis of basic aerodynamic characteristics

As a result of the conducted calculations, the values of aerodynamic force components were obtained: F_X drag forces, F_Y side force and F_Z lift forces generated on individual components of the research object for the considered range of angles of attack α and sideslip angles β . Based on the determined values of the forces, the corresponding aerodynamic coefficients were calculated using Eqs. (1) and (2):

$$C_{X,Y,Z} = \frac{F_{X,Y,Z}}{0.5\rho v^2 \pi R^2} \quad (1)$$

$$C_{MX,MY,MZ} = \frac{M_{X,Y,Z}}{0.5\rho v^2 \pi R^2 l} \quad (2)$$

In order to calculate the coefficients, the following were assumed: an aircraft rotor radius of $R = 1$ m, air density $\rho = 1.2257$ kg/m³ and air velocity $v = 20$ m/s. The reference length l used for calculating the moment coefficients was 1 m. The aerodynamic characteristics of the analyzed object are presented in Fig. 20, Fig. 21 and Fig. 22. They respectively illustrate the dependence of the aerodynamic force components C_X , C_Y , C_Z as well as the aerodynamic moment components C_{MX} , C_{MY} , C_{MZ} as a function of the angle of attack α for various sideslip angles β . Under the adopted coordinate and sign conventions, a negative pitching-moment derivative $dC_{MY}/d\alpha$ was interpreted as a restoring longitudinal aerodynamic response. A negative rolling-moment derivative $dC_{MX}/d\beta$ indicated a restoring lateral response, whereas a positive yawing-moment derivative $dC_{MZ}/d\beta$ indicated a restoring directional response. These criteria refer to the aerodynamic behaviour of the investigated fuselage-empennage airframe about the adopted moment reference point.

An analysis of the drag coefficient C_X reveals its variation with the angle of attack α for a given sideslip angle β . It was demonstrated that for:

- $\beta = 0^\circ$, the values of C_X decrease from 0.0222 at $\alpha = -25^\circ$ to a minimum of 0.00614 at $\alpha = +5^\circ$. They then increase up to 0.0188 for $\alpha = +25^\circ$;
- for $\beta = 5^\circ$, a similar trend is observed, with C_X values decreasing from 0.0225 at $\alpha = -25^\circ$ to a minimum of

0.00660 at $\alpha = +5^\circ$, and then increasing up to 0.0189 at $\alpha = +25^\circ$;

- for $\beta = 10^\circ$, the C_X values decrease from 0.0226 at $\alpha = -25^\circ$ to a minimum of 0.00721 at $\alpha = +5^\circ$, and then increase up to 0.0195 at $\alpha = +25^\circ$;
- for $\beta = 15^\circ$, the C_X values decrease from 0.0235 at $\alpha = -25^\circ$ to a minimum of 0.00799 at $\alpha = 0^\circ$, and then increase up to 0.0205 at $\alpha = +25^\circ$;
- for $\beta = 20^\circ$, the C_X values decrease from 0.0248 at $\alpha = -25^\circ$ to a minimum of 0.00970 at $\alpha = 0^\circ$, and then increase up to 0.0221 at $\alpha = +25^\circ$;
- for $\beta = 25^\circ$, C_X values decrease from 0.0260 at $\alpha = -25^\circ$, reaching a minimum of 0.01204-0.01206 at $\alpha = 0-5^\circ$, and then increase up to 0.0240 at $\alpha = +25^\circ$.

With regard to the influence of the sideslip angle β at a constant angle of attack α , for negative angles of attack (-25° to -5°) the value of C_X increases significantly with increasing β . At $\alpha = -25^\circ$, it ranges from 0.0222 ($\beta = 0^\circ$) to 0.0260 ($\beta = 25^\circ$). For angles close to zero ($\alpha = -5^\circ$ to $+5^\circ$), C_X also increases with β , although the minimum values occur within this α range. For large positive angles of attack ($\alpha \geq 10^\circ$), C_X continuously increases with β . As the sideslip angle β increases, the airflow around the fuselage becomes increasingly asymmetric, resulting in the formation of additional vortices and flow separation regions. As a result, the effective area opposing the flow increases, mainly due to the asymmetric loading of the fuselage side surfaces and the empennage. The extent of this increase depends upon the angle of attack α ; for instance, at $\alpha = +10^\circ$, $+15^\circ$, $+20^\circ$, and $+25^\circ$, the drag coefficient rose by 92%, 63%, 44%, and 27%, respectively. The minimum aerodynamic drag values occur within the range of α from 0° to 5° for most of the analyzed sideslip angles β . This indicates that the XGyro fuselage exhibits the most favourable aerodynamic characteristics within this range of angles of attack, which corresponds to the intended operational range for level flight. An increase in the absolute value of the angle of attack (large $| \alpha |$, both positive and negative) leads to a noticeable rise in aerodynamic drag, which is characteristic of emerging flow separation regions. The sideslip angle β has a significant effect on the level of aerodynamic drag. Even for the same angle of attack, the minimum C_X values systematically increase with rising β . The most streamlined flow condition occurs at $\beta = 0^\circ$,

corresponding to zero sideslip. In summary, the lowest drag coefficient, $C_X = 0.00614$, occurs at $\alpha = +5^\circ$ and $\beta = 0^\circ$. The highest drag coefficient, $C_X = 0.0260$, occurs at $\alpha = -25^\circ$ and $\beta = 25^\circ$.

Analyzing the values of the side force coefficient C_Y , it can be observed that for each sideslip angle β , the variations as a function of the angle of attack α are significant, and the C_Y values increase with increasing β , where for:

- $\beta = 0^\circ$, the C_Y values are very low and oscillate near zero, which confirms the symmetry of the flow.
- $\beta = 5^\circ$, the increase in sideslip angle causes a significant rise in C_Y . The values increase from approximately 0.0015 at $\alpha = -25^\circ$ to a maximum of 0.00651 at $\alpha = 5^\circ$. This trend is clear, and the highest values occur in the range of $\alpha = 0^\circ-5^\circ$, which results from the asymmetric flow around the fuselage;
- $\beta = 10^\circ$, the C_Y values reach levels of approximately 0.009-0.010 within the range of $\alpha = 5^\circ-10^\circ$. The minimum occurs at $\alpha = 25^\circ$. The curve exhibits a clearly increasing trend at low and moderate angles of attack, followed by a decrease at the extreme values;
- $\beta = 15^\circ$, the C_Y values are even higher, reaching a maximum of 0.0131 at $\alpha = 5^\circ$. It is evident that in this sideslip configuration, the fuselage generates a significant side force regardless of the angle of attack, with the values being several times higher than those for $\beta=0^\circ$;
- $\beta = 20^\circ$, C_Y increases further, reaching a maximum of 0.0158 at $\alpha = 10^\circ$. Even at high positive angles of attack, e.g. $\alpha = 25^\circ$, the values remain at the level of 0.0116, which indicates a significant asymmetry of the flow.
- $\beta = 25^\circ$, the highest C_Y value of 0.0187 occurs at $\alpha = 10^\circ$. Throughout the entire range of α , the coefficient remains at a relatively high level (≥ 0.010).

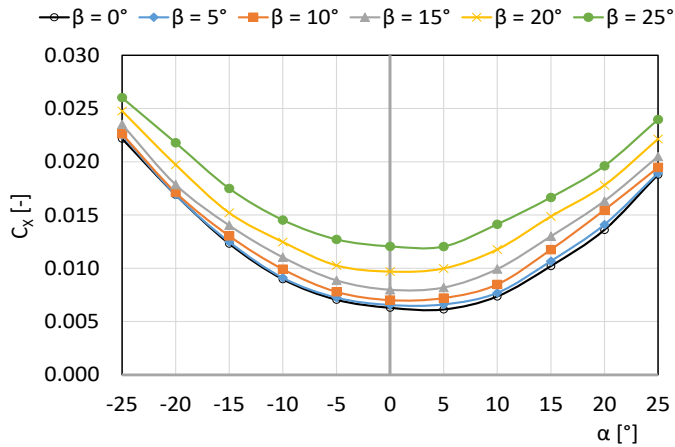
In summary, for nonzero β values, the maximum C_Y typically occurs within the α range of 5° to 10° . At very high $| \alpha |$ values, around $\pm 25^\circ$, the C_Y values decrease, suggesting a change in the flow pattern and a partial reduction of asymmetry. The C_Y value increases almost linearly with β for each angle of attack. An increase in β results in a significant rise in the side force, which is crucial for the analysis of directional stability and the loading of the vertical tail. Minimal values

close to zero occur for $\beta = 0^\circ$. The global maximum of $C_Y = 0.0187$ was obtained at $\beta = 25^\circ$ and $\alpha = 10^\circ$.

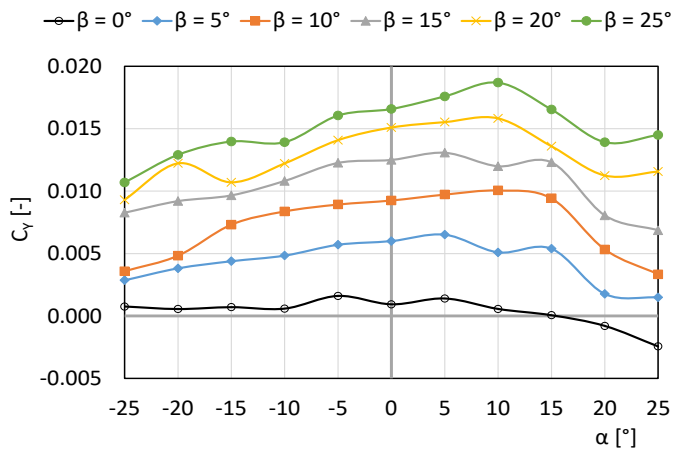
In analyzing the lift coefficient C_Z , attention was given to the influence of the angle of attack α at a constant sideslip angle β . For $\beta = 0^\circ$, the C_Z values increase almost linearly with the angle of attack, from -0.0251 at $\alpha = -25^\circ$, through a value close to zero at $\alpha = -10^\circ$, up to a maximum of 0.0540 at $\alpha = 25^\circ$. The trend is typical for this type of configuration, and in this case, higher angles of attack correctly result in an increase in lift force. For $\beta = 5^\circ$, the trend is very similar, although the values are slightly lower than for $\beta = 0^\circ$. It was possible to observe the extreme values, i.e., a minimum of -0.0253 at $\alpha = -25^\circ$ and a maximum of 0.0523 at $\alpha = 25^\circ$. For $\beta = 10^\circ$, the values increase from -0.0241 at $\alpha = -25^\circ$ to 0.0510 at $\alpha = 25^\circ$. Positive values are reached starting from approximately $\alpha = -8^\circ$. For $\beta = 15^\circ$, the curve is positioned slightly lower than for the smaller β values. The minimum is -0.0227 at $\alpha = -25^\circ$, and the maximum is 0.0495 at $\alpha = 25^\circ$. For $\beta = 20^\circ$ a clear reduction of the lift curve can be observed compared to the $\beta = 0^\circ$. The values range from -0.0207 to 0.0494. For $\beta = 25^\circ$, the curve shows the smallest slope of the characteristic, with a minimum of -0.0182 at $\alpha = -25^\circ$ and a maximum of 0.0481 at $\alpha = 25^\circ$. The lift coefficient C_Z follows the classical characteristic, increasing almost linearly with the angle of attack α . The minimum values occur at $\alpha = -25^\circ$, regardless of the sideslip angle. The maximum values occur at $\alpha = 25^\circ$, and their level decreases as β increases. An increase in the sideslip angle β leads to a decrease in C_Z values across the entire range of angles of attack. This indicates that sideslip adversely affects lift generation efficiency, since the asymmetric flow redirects part of the airflow's kinetic energy towards side force instead of lift. The most favourable lift generation conditions occur in the absence of sideslip ($\beta = 0^\circ$) and at positive angles of attack.

Subsequently, the influence of the angle of attack α on C_{MX} was analyzed for different sideslip angles β . For $\beta = 0^\circ$, the C_{MX} values oscillate around zero. The fuselage shows no natural tendency to roll during straight and level flight. For small sideslip angles (β from 5° to 10°), positive C_{MX} values appear at negative angles of attack (e.g. α from -25° to -5°), indicating the presence of small rolling moments. As α increases, the moment gradually decreases. For larger sideslip angles ($\beta = 15^\circ$ - 25°), the C_{MX} values systematically increase within the range of negative

angles of attack, reaching maxima of approximately 0.0038-0.0043 at $\alpha = -25^\circ$. For positive angles of attack ($\alpha \geq 10^\circ$), the values become distinctly negative, reaching a minimum of -0.0025 at $\alpha = 25^\circ$ and $\beta = 25^\circ$. The highest positive C_{MX} values occur at $\alpha = -25^\circ$ and large sideslip angles ($\beta = 25^\circ$). The most negative values occur at high positive angles of attack, i.e., $\alpha = 25^\circ$ and $\beta = 25^\circ$, where $C_{MX} \approx -0.0025$. It should also be emphasized that an increase in sideslip angle leads to a systematic rise in the absolute value of C_{MX} . This means that the greater the β angle, the more asymmetric the flow becomes, generating a lateral rolling moment. For small β values (0° - 5°), the moments are close to zero, confirming good fuselage symmetry. For large β values (20° - 25°), a clear asymmetry is observed, and the C_{MX} values become significant on both the positive side (for $\alpha < 0^\circ$) and the negative side (for $\alpha > 10^\circ$). In summary, the rolling moment coefficient C_{MX} , in the absence of sideslip ($\beta = 0^\circ$), remains practically at zero across the entire range of α , indicating that the fuselage shows no tendency to roll spontaneously. An increase in sideslip angle induces flow asymmetry, which results in the growth of rolling moments. The largest positive moments occur at high negative angles of attack, whereas the largest negative moments are observed at high positive angles of attack. This phenomenon is of considerable importance from the standpoint of lateral stability. Large sideslip angles may generate destabilizing moments that must be compensated for by the control system. It can be assumed that an increase in β leads to higher absolute values of C_{MX} , which is consistent with physics and indicates that the model responds correctly to lateral disturbances. Although the characteristics are not fully linear across the entire range of the angles of attack, they exhibit noticeable linear tendencies, with no abrupt variations that would suggest flow loss or large-scale separation. For the linear regression at $\beta = 0^\circ$, R^2 equals 0.9927, and for $\beta = 25^\circ$, the R^2 value is equal to 0.9987. This indicates that the error of linear fitting is very small within the examined range of angles of attack. In the operational range (small angles of attack and sideslip), the behaviour is consistent with theoretical expectations and reference patterns reported in the available literature. The deviations observed at high α and β were considered acceptable for this object, as they result from the complexity of the flow.



(a)

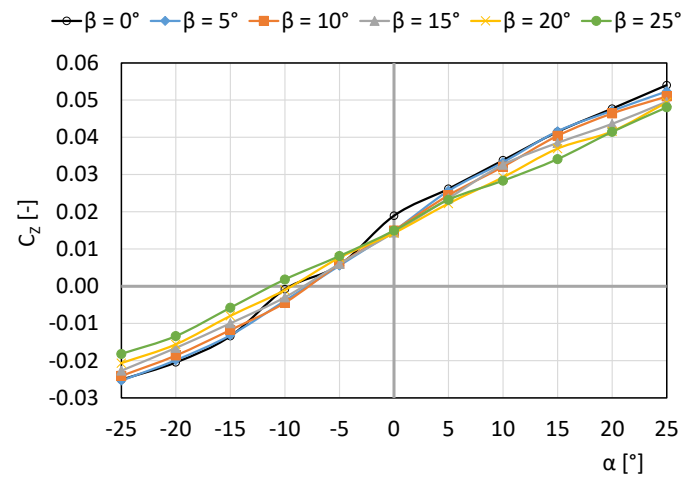


(b)

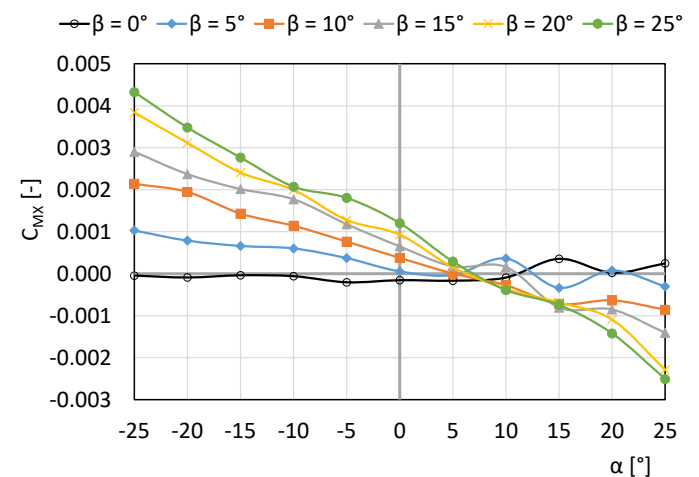
Figure 20. Characteristics of drag force coefficient C_X (a) and side force coefficient C_Y (b) depending upon the angle of attack.

The presented pitching moment coefficient characteristics C_{MY} (see Fig. 22) enable an analysis showing that, for $\beta = 0^\circ$, the coefficient decreases almost linearly with increasing α : from $+0.00824$ (at $\alpha = -25^\circ$) to -0.01021 at $\alpha = +25^\circ$. The zero crossing occurs between $\alpha = -5^\circ$ ($+0.00161$) and $\alpha = 0^\circ$ (-0.00099). The zero crossing of C_{MY} occurs at an angle of attack slightly below 0° and represents a zero-pitching-moment condition of the analysed fuselage–empennage airframe about the adopted moment reference point. Since the main rotor and active propulsion effects were not included, this condition should not be interpreted as the trim condition of the complete XGyro configuration. This indicates a negative derivative $dC_{MY}/d\alpha$ and static stability in the longitudinal operational range. For $\beta = 5^\circ$, the behaviour of the object is very similar. The characteristics range from $+0.00826$ at $\alpha = -25^\circ$ to -0.00985 at $\alpha = +25^\circ$. The zero C_{MY} coefficient also occurs around $\alpha \approx -1^\circ$ to -2° . Linearity is well maintained across the entire range, with minimal

deviation near the mid-range angles of attack. For the next considered sideslip angle $\beta = 10^\circ$, the extreme values are $+0.00778$ ($\alpha = -25^\circ$) and -0.00935 ($\alpha = +25^\circ$), respectively. For $\beta = 15^\circ$, they range from $+0.00735$ ($\alpha = -25^\circ$) to -0.00896 ($\alpha = +25^\circ$). The zero value occurs at approximately $\alpha \approx -2^\circ$. For $\beta = 20^\circ$, the value C_{MY} reaches a maximum of $+0.00664$ ($\alpha = -25^\circ$) and a minimum of -0.00861 ($\alpha = +25^\circ$). For $\beta = 25^\circ$, the corresponding values are $+0.00551$ ($\alpha = -25^\circ$) and -0.00784 ($\alpha = +25^\circ$). This characteristic exhibits the smallest range of values, representing the most “flattened” curve. Taking the above into account, it can be concluded that a higher sideslip angle β reduces longitudinal sensitivity (lowering $|dC_{MY}/d\alpha|$), since flow asymmetry and the contribution of side forces partially “unload” the system along the longitudinal axis, shifting the resultant forces and moments.



(a)



(b)

Figure 21. Characteristics of lift force coefficient C_Z (a) and roll moment coefficient C_{MX} (b) depending upon the angle of attack.

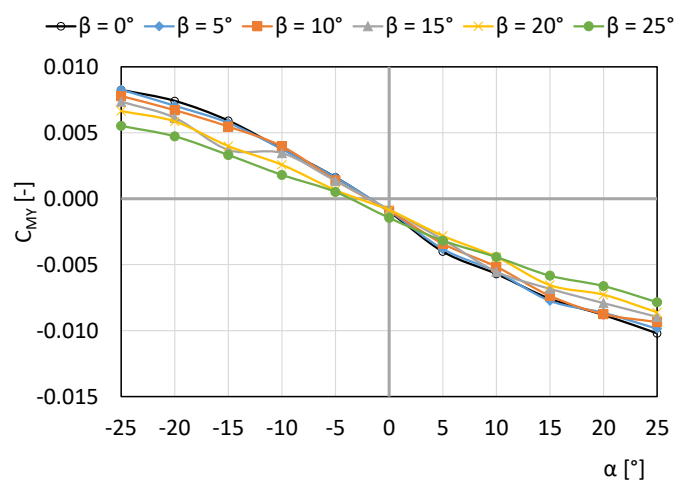
In all β series, the derivative $dC_{MY}/d\alpha$ takes negative values over a wide range of α , which is a clear indication of longitudinal stability (an increase in α produces a restoring negative moment, while a decrease in α produces a positive one). The $dC_{MY}/d\alpha$ values are typical for slender fuselages with empennage. An increase in β reduces the absolute slope (milder characteristics) but does not reverse the sign of C_{MY} within the operational range. The system remains stable, although with reduced stability margin at high sideslip angles. The neutral angle of attack α , at which $C_{MY}=0$, lies slightly below 0° for all β (typically between -3° and -1°), which is consistent with the expectation that even at small positive α , lift is generated by the fuselage/empennage along with a restoring moment.

The yawing moment coefficient C_{MZ} exhibits the expected behaviour. During a symmetric flight ($\beta = 0^\circ$), it remains practically zero, and with an increasing sideslip angle, it assumes positive values that grow with the angle of attack. The range of variation is moderate (up to approximately 0.0024), indicating the absence of significant aerodynamic asymmetries in the fuselage. The characteristics are smooth and monotonic, indicating proper aerodynamic behaviour. The absence of yawing moments at $\beta = 0^\circ$ confirms the accuracy of the geometric model, its symmetry, as well as the correctness of the very calculations. An increase in the sideslip angle β induces asymmetric flow around the fuselage and the vertical tail, leading to an increase in positive C_{MZ} moments. The values are proportional to β and remain small, suggesting that the fuselage does not generate excessive yawing moments, and that directional control is primarily provided by the vertical tail.

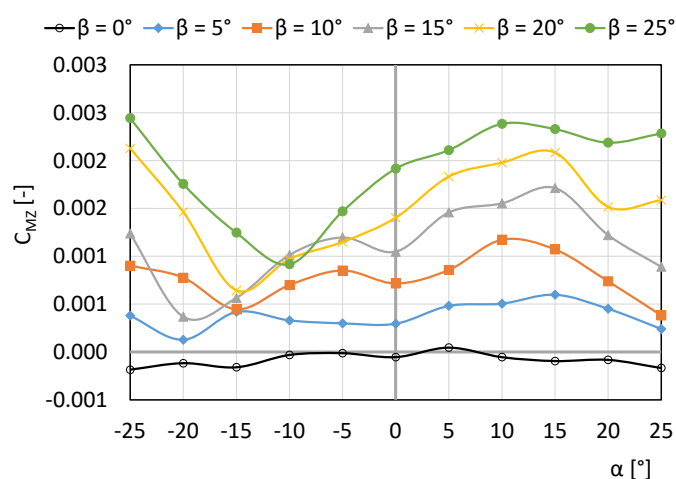
Fig. 23 shows the lift force coefficient versus the drag force coefficient. All characteristics exhibit a typical behaviour for aircraft configurations. At low drag values, lift increases with only a slight increase in drag, whereas at higher angles of attack, the curves tend to flatten. This indicates that further increases in lift come at the cost of a rapid rise in drag. This is a classic manifestation of reduced aerodynamic efficiency. The following conclusions can be drawn for the individual sideslip angles:

- $\beta = 0^\circ$: the curve is most favourable, as the lowest C_Z corresponds to the smallest C_X value. This means that the absence of sideslip provides the highest aerodynamic efficiency.

- $\beta = 5^\circ$ and $\beta = 10^\circ$: the curves shift to the right, indicating an increase in drag while maintaining similar lift values. The aerodynamic efficiency of the system decreases.
- $\beta = 15^\circ$: the characteristics are further shifted toward higher C_X values, and the slope of the curve becomes smaller. This indicates a reduction in the C_Z/C_X ratio associated with increased flow asymmetry and additional drag around the fuselage–empennage configuration.
- $\beta = 20^\circ$ and $\beta = 25^\circ$: for the highest sideslip angles, the curves shift noticeably away from the vertical axis, showing a rapid increase in drag with only a moderate increase in lift. The C_X values for a given C_Z are the highest, confirming the strongly adverse effect of sideslip on aerodynamic efficiency.



(a)

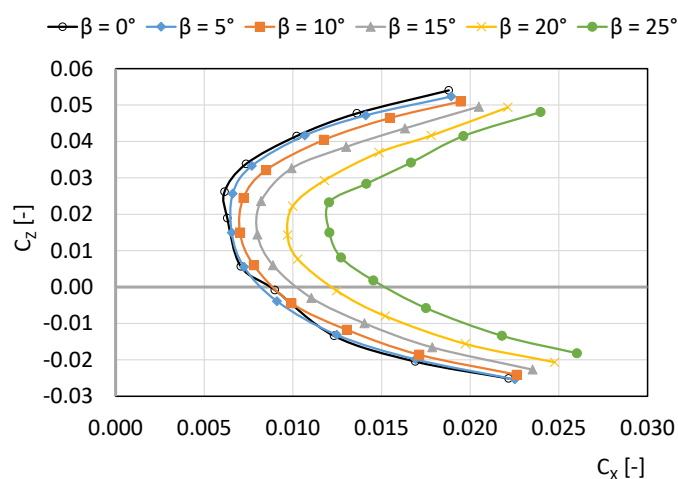


(b)

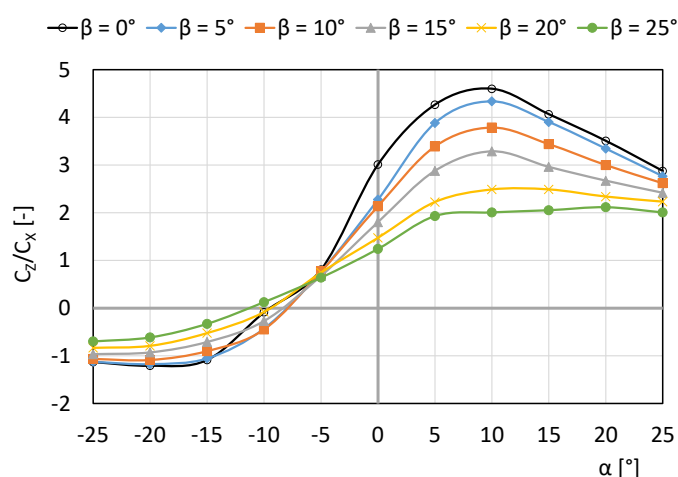
Figure 22. The characteristics of pitch moment coefficient C_{MY} (a) and yaw moment coefficient C_{MZ} (b) depending upon the angle of attack.

The highest C_Z/C_X ratios (maximum aerodynamic efficiency) are achieved at small angles of attack and $\beta = 0^\circ$. As β increases, the maximum aerodynamic efficiency systematically decreases, due to the increase in drag associated with asymmetric flow and local separation around the fuselage and empennage. At high sideslip angles ($\beta \geq 20^\circ$), aerodynamic efficiency drops by nearly half compared to the baseline case ($\beta = 0^\circ$), indicating a significant deterioration of aerodynamic performance.

An increase in sideslip angle leads to a rise in drag, mainly associated with the previously identified key regions, as well as changes in the flow pattern around the empennage and fuselage. As a result, the $C_Z(C_X)$ curves shift to the right and their slope decreases.



(a)



(b)

Figure 23. Lift force coefficient versus drag force coefficient (a) and lift-to-drag ratio versus angle of attack of the research model (b).

For small sideslip angles ($\beta \leq 15^\circ$), the optimum occurs at $\alpha \approx 10^\circ$. This is the point where C_Z is already high, while C_X

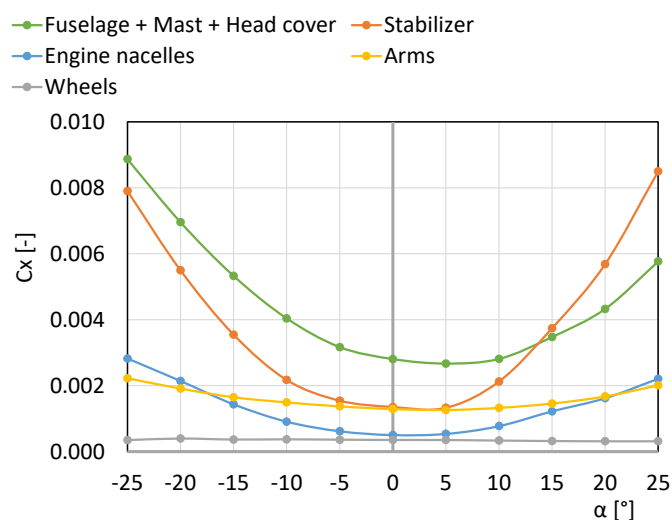
remains relatively low. Hence, the highest aerodynamic efficiency is achieved. As β increases, aerodynamic efficiency systematically decreases (from 4.60 to 2.12), and the optimum point shifts towards higher α . For $\beta = 20^\circ$, it is 15° , and for $\beta = 25^\circ$, it reaches 20° . The lateral inflow increases drag and degrades the efficiency of lift generation, therefore a higher angle of attack is required to recover part of the lost lift. The decrease in aerodynamic efficiency with increasing sideslip angle β is quite rapid. This confirms the earlier observation that sideslip is the primary factor degrading the aerodynamic efficiency of the fuselage during oblique flight.

4.1.3. Analysis of the contribution of structural components to the generation of aerodynamic drag

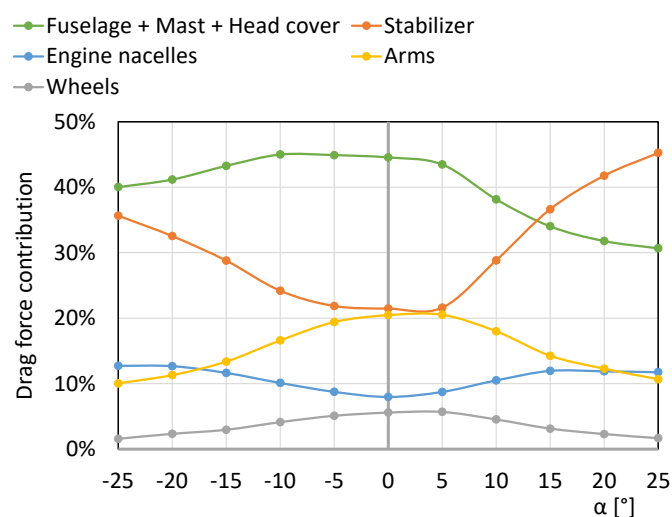
One of the major advantages of CFD methods compared to conventional wind tunnel testing is the ability to precisely isolate the contribution of individual components of the analyzed object, e.g. to the overall aerodynamic drag. In experimental studies conducted in a wind tunnel, the measured quantities typically include the total forces and moments acting on the entire model as a whole, which limits the identification of drag sources to qualitative analysis, flow visualization methods (e.g., smoke, PIV, or oil-flow techniques), or additional specialized measurement procedures that require modifications of the model's structure.

In the case of CFD, each geometric component is treated as a separate computational surface, enabling the direct calculation of the aerodynamic force distribution acting on the fuselage, empennage, landing gear, and auxiliary elements. This feature makes it possible not only to determine the contribution of individual components to the total drag force, but also to assess their mutual influence on the flow and to identify critical regions associated with adverse aerodynamic phenomena. As a result, CFD enables a more detailed analysis and serves as a complementary tool for wind tunnel testing, supporting the structural optimization process prior to the construction of a physical model. Although the contribution of individual components to the total aerodynamic drag is of key importance, this article, due to space limitations, presents results only for the sideslip angle $\beta = 0^\circ$, corresponding to the case of symmetric flow. The analysis was conducted on the final geometry of the object, and the results were compiled into five grouped

components (Fig. 24). The analysis was divided into the following components: (1) fuselage with mast and head cover, (2) stabilizer, (3) engine nacelles, (4) arms and (5) wheels.



(a)



(b)

Figure 24. Contributions of the structural components to the total drag coefficient C_X (a) and their relative contributions to total aerodynamic drag (b).

Several key observations can be drawn from the above results. There is a dominant contribution from the fuselage together with the mast and the head fairing. Over the entire range of angles of attack, this component accounts for the largest portion of drag, particularly at large negative and positive α values (e.g. at $\alpha = -25^\circ$, it contributes approximately 40% of the total C_X , and at $\alpha = +25^\circ$, it is approximately 31%). There is also a significant contribution of the empennage, which increases noticeably at positive angles of attack. At $\alpha = +25^\circ$, the empennage generates more drag than the fuselage with mast and

head fairing (8.5×10^{-3} vs 5.76×10^{-3}), highlighting its significant role in the overall aerodynamic balance. The engine nacelles and arms have a moderate but relatively stable contribution. Their values increase with α , but even at high angles, e.g. $\alpha = +25^\circ$, their contribution does not exceed 12% of the total drag. Their maximum contribution occurs at $\alpha = 0^\circ$ and amounts to 20.5%. The contribution of the wheels to the total drag is the smallest. Irrespective of the angle of attack, their contribution varies within the range of $3.1\text{--}3.9 \cdot 10^{-4}$, accounting for only a few percent of the total drag.

4.2. Wind tunnel test results

Compared to the CFD simulations, in the case of the wind tunnel testing, the range of angles of attack was limited to $\alpha = -20^\circ$ to $+20^\circ$, in 5° increments, while the sideslip angle was varied from 0° to $+20^\circ$, every 5 degrees. When analyzing the drag coefficient C_X values obtained from the wind tunnel tests (see Fig. 25), a clear dependence of their variation on the angle of attack α is observed for each of the analyzed sideslip angles β :

- $\beta = 0^\circ$, the C_X values drop from 0.0165 at $\alpha = -20^\circ$ to a minimum of 0.0051 at $\alpha = 0^\circ$, and then increase up to 0.0184 at $\alpha = +20^\circ$. The minimum occurs at small angles of attack, which corresponds to the optimal flow around the fuselage.
- $\beta = 5^\circ$: the C_X values also decrease from 0.0152 ($\alpha = -20^\circ$) to a minimum of 0.0054–0.0060 ($\alpha = 0^\circ$ – 5°), and then increase up to 0.0185 at $\alpha = +20^\circ$.
- $\beta = 10^\circ$, the C_X values drop from 0.0169 at $\alpha = -20^\circ$ to a minimum of 0.0062 at $\alpha = 0^\circ$, and then increase up to 0.0191 at $\alpha = +20^\circ$.
- $\beta = 15^\circ$, the coefficient starts at 0.0172 ($\alpha = -20^\circ$), decreases to 0.0075 at $\alpha = 0^\circ$, and then increases to 0.0203 at $\alpha = +20^\circ$.
- $\beta = 20^\circ$, the C_X values are noticeably higher, starting from 0.0171 at $\alpha = -20^\circ$, decreasing to a minimum of 0.0097 at $\alpha = 0^\circ$, and then increasing to 0.0218 at $\alpha = +20^\circ$.

For all sideslip angles, the characteristics exhibit a parabolic shape. The minimum C_X values occur within the range of $\alpha = 0^\circ \pm 5^\circ$. Both large negative and positive angles cause a distinct increase in drag, which is associated with intensified flow separation. Along with increasing β , the C_X value for a given

angle of attack increases systematically. The differences are particularly noticeable near the minima; for example, at $\alpha = 0^\circ$, the drag increases from 0.0051 for $\beta = 0^\circ$ to 0.0097 for $\beta = 20^\circ$, representing an increase of approximately 90%. This indicates that the presence of a sideslip angle significantly increases aerodynamic drag, resulting from asymmetric flow and the development of lateral vortex regions, primarily associated with the fuselage and empennage. The wind tunnel tests confirm the characteristic behaviour of the C_X coefficient:

- the minimum drag occurs within the range of $\alpha = 0^\circ \pm 5^\circ$,
- C_X values increase sharply at high angles of attack, both positive and negative.
- The sideslip angle β clearly increases the drag level - the greater the flow asymmetry, the larger the rise in C_X .
- The lowest recorded drag coefficient is $C_X = 0.0051$ at $\alpha = 0^\circ$, $\beta = 0^\circ$; the highest drag coefficient $C_X = 0.0218$, occurs at $\alpha = +20^\circ$ and $\beta = 20^\circ$.

The side force coefficient C_Y , also shown in Fig. 25, appears correct and behaves as expected. For $\beta = 0^\circ$, the values remain close to zero over the entire range of α , which indicates aerodynamic symmetry in the absence of sideslip. As β increases, the value of the side force grows; for example, at $\alpha = 0^\circ$, it ranges from -0.00074 ($\beta = 0^\circ$) to 0.01822 ($\beta = 20^\circ$). It is evident that changes in β directly generate a side force, the value of which increases almost linearly with the sideslip angle.

For all analyzed sideslip angles (β from 0° to 20°), the $C_Z(\alpha)$ curves are smooth and increase monotonically with the angle of attack (Fig. 26). For $\beta = 0^\circ$, the C_Z value ranges from -0.020 at $\alpha = -20^\circ$ to 0.0480 at $\alpha = 20^\circ$. Within the range of α from -10° to $+15^\circ$, the characteristics are nearly linear. The approximate lift-curve slope is $dC_Z/d\alpha \approx 0.0019/\text{deg}$ (approx 0.11/rad.) The zero lift angle is approximately -9° . At $\beta = 5^\circ$, the C_Z values are very close to those at $\beta = 0^\circ$. The minimum C_Z value is -0.0160, and the maximum is 0.0483. The section corresponding to α values from -10° to $+15^\circ$ is also quasi-linear. For the remaining sideslip angles β , the C_Z values range from -0.0177 to 0.0486 for $\beta = 10^\circ$, from -0.0145 to 0.0471 for $\beta = 15^\circ$, and from -0.0114 to 0.04636 for $\beta = 20^\circ$. With increasing sideslip angle β , the zero-lift angle of attack α_0 shifts toward more negative values; for instance, at $\beta=20^\circ$, it reaches $\alpha_0 = -12^\circ$. For negative α values, increasing β results in a decrease in the absolute value of C_Z (for instance, at $\alpha = -20^\circ$, C_Z decreases from

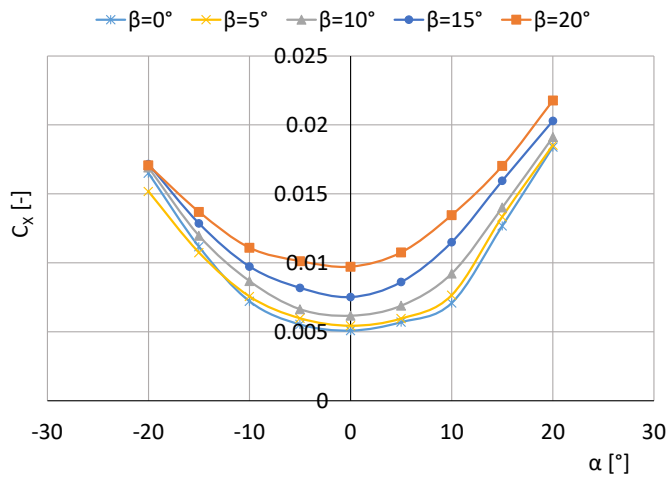
-0.0200 for $\beta = 0^\circ$ to -0.0115 for $\beta = 20^\circ$). This indicates an upward shift of the curve towards the zero-lift condition, which is associated with the fact that the lateral flow component resulting from the sideslip partially unloads the lift on the fuselage and wings. At small positive α values (from 0° to 10°), the differences between the curves are small, on the order of 0.0005–0.002. All the curves remain nearly parallel. At high positive α values (from 15° to 20°), an increase in β results in a slight decrease in C_Z ; for example, at $\alpha = 20^\circ$, changing β from 0° to 20° reduces the coefficient from 0.0480 to 0.04636, by approximately 3-4%. This trend is moderate and does not alter the overall shape of the curves. Therefore, the influence of β on the maximum C_Z is small (several percent), with a slight decrease at higher sideslip angles. From the flight envelope perspective, this indicates a stable lift margin even at moderate sideslip angles.

Another analyzed coefficient is C_{MX} , whose characteristics at $\beta = 0^\circ$ remain very close to zero throughout the entire range of α . This is consistent with the symmetry of the model, as no significant rolling moment should arise in the absence of sideslip. For $\beta = 5^\circ$, at negative α values, the C_{MX} value is positive; it then decreases, crosses zero between $\alpha \approx 0^\circ$ and 5° , and becomes negative for positive α . The $C_{MX(\alpha)}$ relationship is almost linear within the range of -10° to 15° . The same trend is observed for $\beta = 10^\circ$, but with a greater amplitude. For $\beta = 15^\circ$, the C_{MX} values increase for negative angles of attack (reaching a maximum of +0.00206 at $\alpha = -20^\circ$) and then systematically decrease to -0.00228 at $\alpha = 20^\circ$. For $\beta = 20^\circ$, the sensitivity to α is the highest, with the coefficient values changing from +0.00245 at $\alpha = -20^\circ$ to -0.00270 at $\alpha = 20^\circ$.

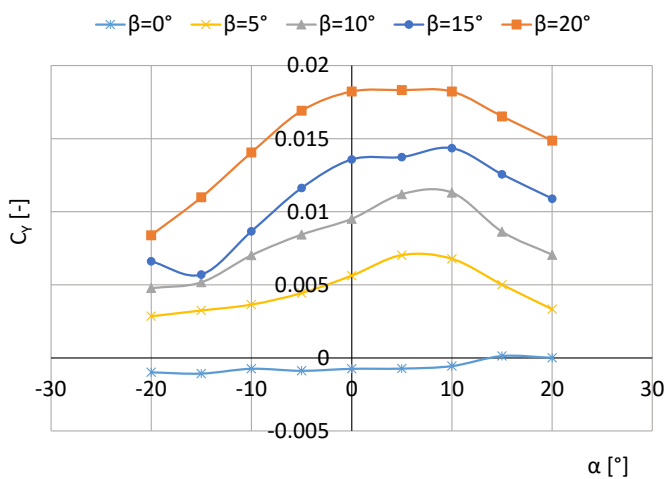
Considering the results in terms of lateral stability, for $\beta = 0^\circ$, there is no significant rolling moment, which indicates that the model maintains the expected symmetry. In contrast, for $\beta > 0^\circ$, a clear, monotonic $C_{MX(\alpha)}$ response appears, crossing zero near $\alpha \approx 0^\circ$. The sign of C_{MX} changes in a predictable manner, and its magnitude increases with the sideslip angle. The configuration generates restoring moments consistent with the design expectations. The obtained results confirm the validity of the tunnel model and provide useful derivatives for the linearization of roll dynamics in stability and control analyses.

The analysis of C_{MY} shows that for $\beta = 0^\circ$, the characteristics decrease monotonically throughout the entire investigated range

of α (Fig. 27). Zero values of this coefficient occur at angles of attack α slightly below 0° for all considered sideslip angles. For $\beta = 5^\circ$, the characteristic curve is practically parallel to $\beta = 0^\circ$. Moreover, it exhibits a linear trend near the zero value. The intersection with the zero coefficient value shifts slightly towards lower α values. The range of the obtained values extends from $+0.00848$ at $\alpha = -20^\circ$ to -0.00933 at $\alpha = +20^\circ$. For $\beta = 10^\circ$, the values vary from $+0.00794$ at $\alpha = -20^\circ$ to -0.00888 at $\alpha = +20^\circ$. The coefficient reaches zero at an angle of attack of approximately $\alpha = -1^\circ$. For $\beta = 15^\circ$, the values range from $+0.00664$ to -0.00826 . Except for $\alpha = 0^\circ$, the smallest absolute values of the coefficient within the entire dataset occur for $\beta = 20^\circ$ (e.g. -0.00798 at $+20^\circ$). The overall characteristics exhibit a lower slope for $\beta = 0^\circ$.

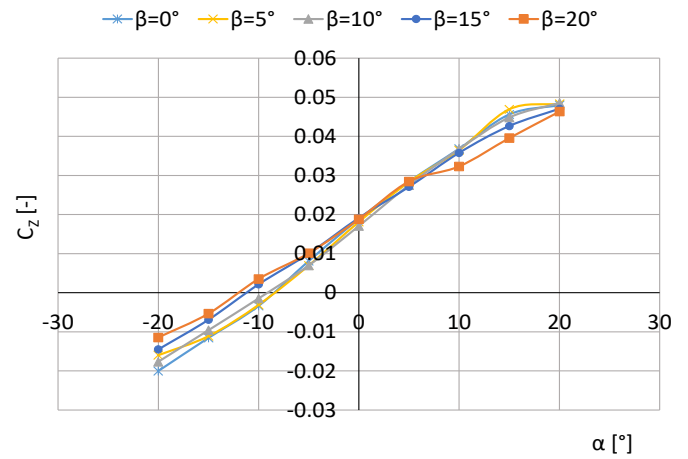


(a)

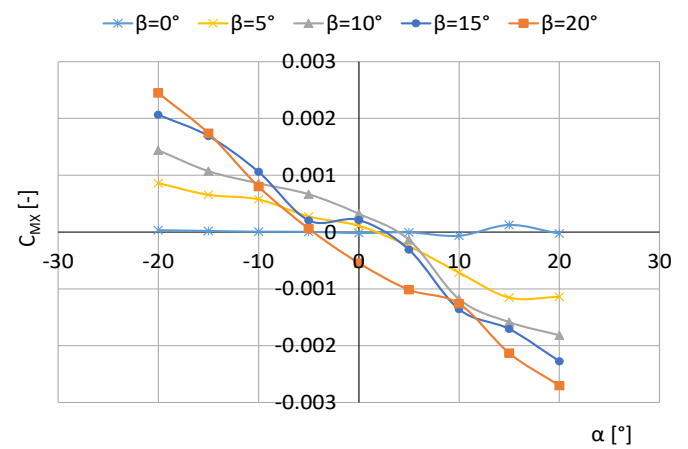


(b)

Figure 25. Characteristics of drag force coefficient C_x (a) and side force coefficient C_y (b) depending upon the angle of attack.



(a)

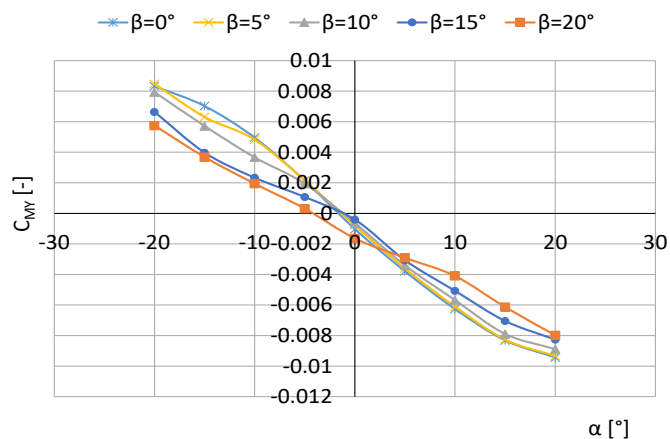


(b)

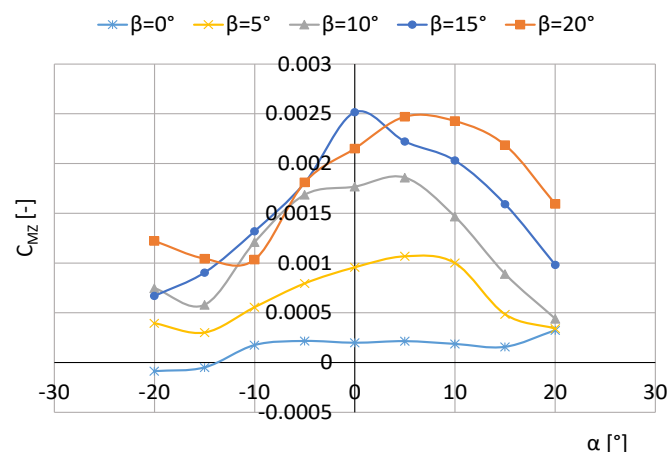
Figure 26. Characteristics of lift force coefficient C_z (a) and roll moment coefficient C_{Mx} (b) depending upon the angle of attack.

The yawing moment coefficient C_{Mz} for $\beta = 0^\circ$ values are close to zero. This indicates that, in the absence of lateral flow, the fuselage symmetry prevents the generation of a significant yawing moment. As β increases, C_{Mz} values rise systematically, reaching a maximum within the sideslip angle range of 15° to 20° . For example, at $\alpha = 0^\circ$, C_{Mz} increases from 0.00020 at $\beta = 0^\circ$ to 0.00215 at $\beta = 20^\circ$. The rate of increase indicates that the yawing moment generated by the flow asymmetry is accurately represented. At zero sideslip angle, the changes are minimal, and the curve remains near a coefficient value of zero. At higher β , changes in α gradually increase C_{Mz} values up to a certain maximum, followed by a slight decrease at higher positive angles. For example, at $\beta = 15^\circ$, the value rises from $C_{Mz} = 0.00067$ at $\alpha = -20^\circ$ to $C_{Mz} = 0.00222$ at $\alpha = 5^\circ$. It then decreases to $C_{Mz} = 0.00098$ at $\alpha = 20^\circ$. The distribution of the obtained values indicates that the largest yawing moments occur at

positive angles of attack and high sideslip angles. The C_{MZ} characteristics confirm an accurate representation of the vehicle's directional stability. The increase in yawing moment with β is consistent with expectations, indicating that at higher sideslip angles, the model generates progressively stronger restoring moments.



(a)

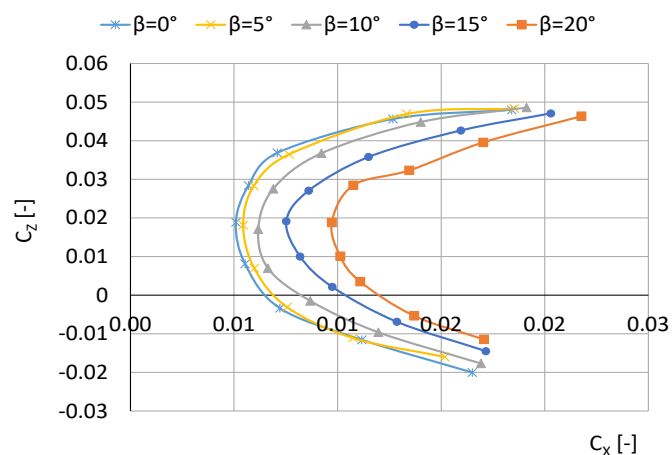


(b)

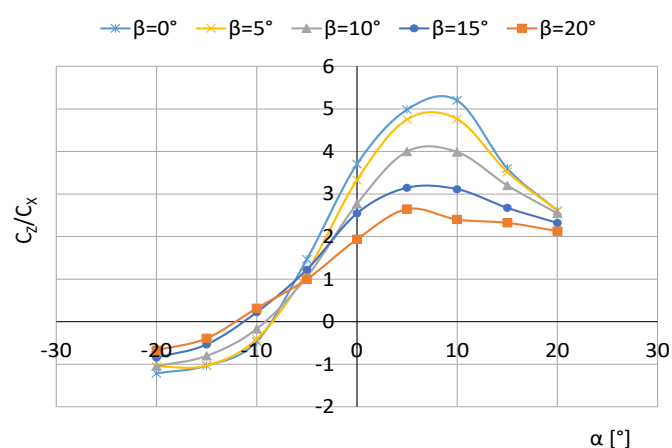
Figure 27. Characteristics of pitch moment coefficient C_{MY} (a) and yaw moment coefficient C_{MZ} (b) depending upon the angle of attack.

The lift force coefficient versus drag force coefficient as well as the lift-to-drag ratio versus angle of attack are presented below (Fig. 28). For all values of β , a typical shape of the curves was obtained: as the lift force increases, the drag force also increases, indicating a compromise between these aerodynamic effects. As β increases, the curves shift to the right, indicating higher drag at similar lift values. This corresponds to a reduction in aerodynamic efficiency. In the central angle of attack range α (from -5° to 10°), the relationships are the most regular. At high α values ($\pm 20^\circ$), lift saturates and drag increases more rapidly.

The highest aerodynamic efficiency, with $C_Z/C_X \approx 5.2$, was achieved at $\beta = 0^\circ$ and $\alpha = 10^\circ$. As the sideslip angle β increases, the maximum aerodynamic efficiency systematically decreases, reaching only 2.65 at $\beta = 20^\circ$. For small sideslip angles, the optimum occurs at a higher angle of attack ($\alpha = 10^\circ$), whereas for larger sideslip angles, the optimum shifts toward $\alpha = 5^\circ$.



(a)

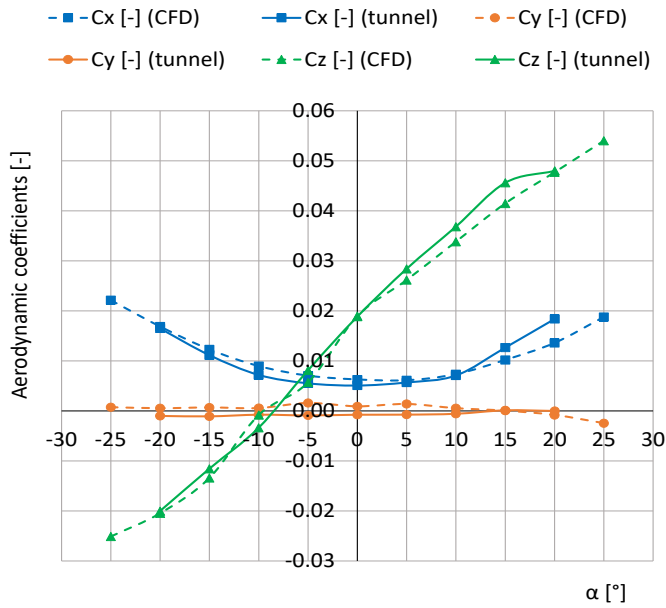


(b)

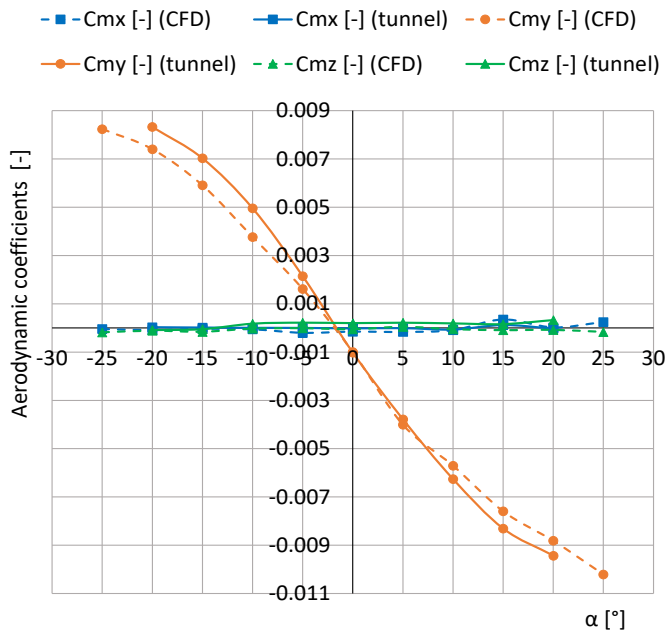
Figure 28. Lift force coefficient versus drag force coefficient (a) and lift-to-drag ratio versus angle of attack of the research model (b).

4.3. Comparison of CFD and wind tunnel results

The following section presents a comparison between CFD and wind tunnel results obtained for the analysed configuration. For the comparison of the applied methods, various sideslip angles could be analyzed; however, the analysis was limited to the zero sideslip angle and the full range of angles of attack. It should be noted that in the CFD approach, the analysis was carried out for a wider range of angles of attack, i.e. from -25° to 25° .



(a)



(b)

Figure 29. Comparison of aerodynamic force coefficients (a) and aerodynamic moment coefficients of the research model (b) obtained from CFD simulations and wind tunnel tests for the selected sideslip angle $\beta=0^\circ$.

Fig. 29 presents comparative characteristics of the aerodynamic force coefficients and aerodynamic moment coefficients of the research model obtained using both the CFD method and wind tunnel testing. By comparing the results obtained from the numerical approach with the experimental findings, the following conclusions were formulated:

- the drag coefficient C_X for the analyzed data shows very

good agreement in terms of both trend and numerical values. The minimum C_X values occur near $\alpha = 0^\circ$ (for CFD $C_X = 0.0063$, for wind tunnel $C_X = 0.0051$), and then increase with both positive and negative angles of attack. The absolute differences between the methods do not exceed a few thousandths, which is acceptable and confirms the reliability of the CFD model.

- The side force coefficient C_Y for the analyzed data in both methods assumes small values, close to zero, confirming the symmetry of the configuration in the absence of sideslip. Across the entire range of angles, a consistent trend is observed, with no significant deviations from zero.
- The lift coefficient C_Z exhibits qualitatively consistent values for both methods. It increases as a function of the angle of attack, from negative values at $\alpha = -20^\circ$ to positive values at $\alpha = 20^\circ$. The rate of increase is identical ($dC_Z/d\alpha \approx 0.0019/\text{deg}$). The maximum differences in absolute values fall within the range of 5–10%, which confirms a high level of consistency.
- The rolling moment coefficient C_{MX} , obtained from both CFD simulations and wind tunnel experiments, shows very small values (the order of 10^{-5} – 10^{-4}) across nearly the entire range of the angles of attack. The small differences observed suggest that the rolling moment does not play a dominant role in the analyzed configuration. The sign discrepancies are most likely attributed to the sensitivity of the characteristics to boundary conditions in the numerical and experimental approaches, rather than to an actual aerodynamic effect.
- The C_{MY} coefficient agrees well in both trend and magnitude. Both datasets are characterized by positive pitching moments at negative angles of attack and a transition to negative values at positive α . The derivative $dC_{MY}/d\alpha$ in the vicinity of zero angle of attack is approximately $-0.0005/\text{deg}$. for the CFD results. An almost identical value was obtained in the wind tunnel tests, confirming that the experimental measurements validate the numerical predictions.
- In both cases, the yawing moment coefficient C_{MZ} exhibits very low values, confirming the proper symmetry of the vehicle in the absence of a sideslip angle.

The CFD and wind tunnel results are consistent in both trend and magnitude. Minor discrepancies may result from the sensitivity of the measurements to slight asymmetries in the wind tunnel.

The slightly larger discrepancies observed for the moment coefficients can be attributed to their higher sensitivity to local flow phenomena and to the distribution of aerodynamic forces relative to the reference point. While drag and lift coefficients are mainly determined by the overall pressure distribution, moment coefficients depend more strongly on local pressure gradients, separation regions, and small differences in model alignment or mounting. Therefore, minor discrepancies between the numerical and experimental setups may have a more pronounced influence on C_{MX} , C_{MY} , and C_{MZ} than on C_X and C_Z . Although the geometric blockage ratio was relatively limited under the reference condition, the projected area and the associated blockage increase at non-zero angles of attack and sideslip. Flow confinement can therefore affect the measured aerodynamic loads, particularly the drag and moment coefficients. In addition, the external model-support system generates its own aerodynamic drag and modifies the local flow around the lower part of the model. Since neither the wind-tunnel walls nor the external support system were included in the free-stream CFD model, these differences between the experimental and numerical configurations represent a potential source of the remaining quantitative discrepancies.

Table 1. Quantitative comparison of CFD and wind tunnel results for selected aerodynamic coefficients ($\beta = 0^\circ$).

AoA [°]	C_X [-]			C_Z [-]			C_{MY} [-]		
	Absolute difference Δ_{Abs}	Relative difference Δ_{Rel} [%]	Absolute difference Δ_{Abs}	Relative difference Δ_{Rel} [%]	Absolute difference Δ_{Abs}	Relative difference Δ_{Rel} [%]	Absolute difference Δ_{Abs}	Relative difference Δ_{Rel} [%]	Absolute difference Δ_{Abs}
-20	0.0004	2.39%	0.0004	2.10%	0.0009	11.07%			
-15	0.0012	10.30%	0.0019	16.03%	0.0011	15.93%			
-10	0.0018	24.52%	0.0026	76.29%	0.0012	24.00%			
-5	0.0015	27.45%	0.0024	29.96%	0.0005	24.66%			
0	0.0012	23.65%	0.0001	0.51%	0.0000	2.85%			
5	0.0004	7.67%	0.0022	7.85%	0.0002	6.06%			
10	0.0003	3.84%	0.0030	8.15%	0.0006	8.83%			
15	0.0025	19.46%	0.0041	9.08%	0.0007	8.64%			
20	0.0048	26.06%	0.0003	0.62%	0.0006	6.55%			

Fig. 30 presents a comparison of the C_Z - C_X aerodynamic polar and the lift-to-drag ratio C_Z/C_X as a function of the angle of attack. Both methods exhibit a very similar trend. Initially, the C_Z values are negative (for negative angles of attack), then cross zero and increase to positive values at higher angles of attack. In the wind tunnel tests, slightly higher C_Z values were

obtained for the same C_X in the range of moderate and positive angles of attack, suggesting a more favourable aerodynamic efficiency under real conditions. The CFD results accurately reproduce the overall trend but slightly underestimate the increase in C_Z at small positive angles of attack.

When comparing the aerodynamic efficiency ratio C_Z/C_X for

CFD and wind tunnel tests, the maximum value in both cases was observed at $\alpha = 10^\circ$. Due to the differences in the lift and drag coefficients mentioned above, an aerodynamic efficiency of approximately $C_Z/C_X \approx 4.60$ was obtained for the CFD method, and $C_Z/C_X \approx 5.20$ for the wind tunnel tests. It can be observed that both methods yield very similar results in terms of the aerodynamic optimum.

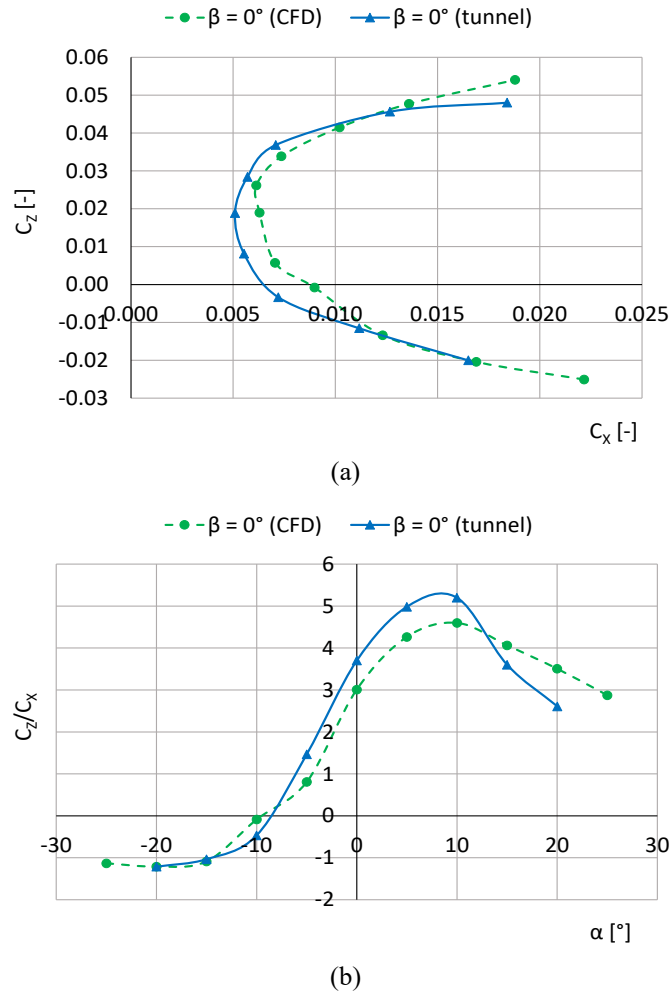
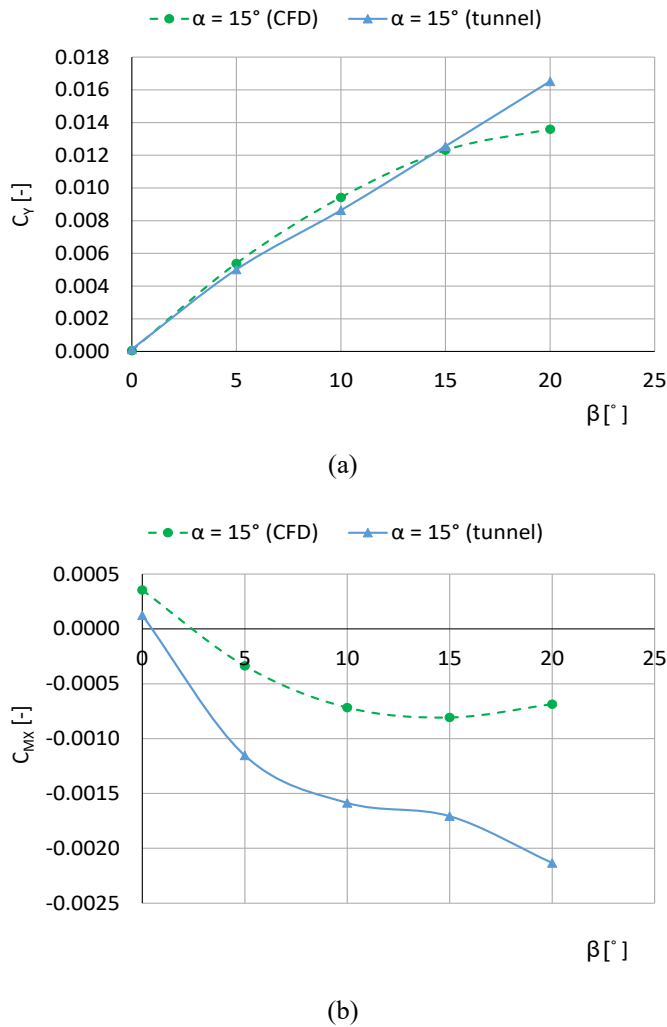
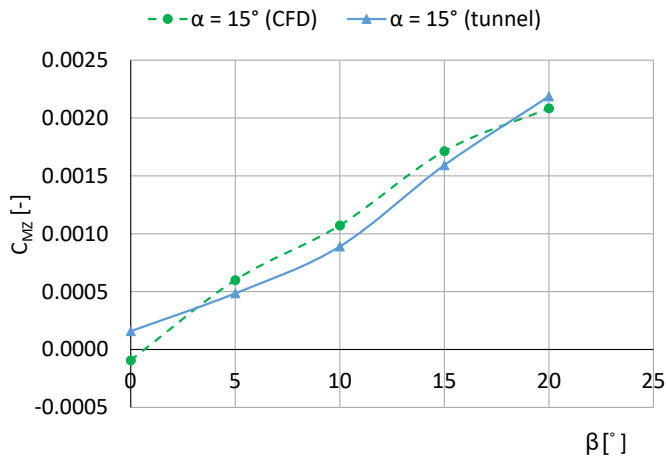


Figure 30. Comparison of the C_Z – C_X aerodynamic polar (a) and the lift-to-drag ratio C_Z/C_X as a function of the angle of attack (b) obtained from CFD and wind-tunnel tests at $\beta=0^\circ$.

To directly assess the agreement in the lateral-directional response, the coefficients C_Y , C_{MX} and C_{MZ} were additionally compared as functions of the sideslip angle β at $\alpha=15^\circ$ (Fig. 31). The selected angle of attack represents conditions under which the lateral-directional response is clearly developed and the values of the analysed coefficients are sufficiently large to reduce the relative influence of discrepancies associated with near-zero quantities. The CFD and wind-tunnel results show a consistent increase in C_Y with increasing β , with good quantitative agreement, particularly over the range $\beta = 5$ – 15° .

For C_{MX} both methods reproduce the same general trend, namely a transition from a value close to zero at $\beta=0^\circ$ to negative values at non-zero sideslip angles, although the experimental values have a greater magnitude. The larger discrepancies observed for C_{MX} result from its high sensitivity to the local distribution of aerodynamic forces and their moment arms relative to the reference point. Consequently, even small differences in the center of pressure location may cause noticeable changes in the rolling moment, while having a considerably smaller influence on the side-force coefficient C_Y . Since the C_{MX} values are small, minor absolute differences also translate into large relative discrepancies. The best agreement was obtained for C_{MZ} , which increases consistently with the sideslip angle in both methods. The slight difference in sign at $\beta=0^\circ$ concerns values of the order of 10^{-4} , which are substantially smaller than those obtained at non-zero sideslip angles. The comparison therefore confirms agreement in the principal trends of the lateral-directional response of the investigated airframe.





(c)

Figure 31. Comparison of the lateral-directional response coefficients of the XGyro fuselage-empennage configuration obtained from CFD and wind-tunnel tests as a function of sideslip angle β at $\alpha=15^\circ$.

When analyzing the above data, it should be noted that the results of CFD numerical analyses and wind tunnel measurements do not always fully coincide. The most common sources of discrepancies include simplifications adopted in the computational models, such as assumptions regarding boundary conditions, turbulence parameters, and the adopted discretization and meshing methods. Turbulence model limitations also play a significant role, as their accuracy in representing real flow phenomena can vary depending on the application, especially in regions of flow separation and strong pressure gradients, such as the fuselage-empennage junction and the wake region behind the fuselage. On the other hand, experimental conditions in the wind tunnel may also differ from the idealizations used in simulations. Experimental discrepancies may also result from gaps and surface imperfections in the model, as well as from small variations in flow velocity, turbulence intensity, and model alignment. However, one should not expect a complete agreement between CFD results and experimental measurements. The purpose of calibration and validation is to achieve an acceptable level of agreement, enabling the use of the numerical model for design analyses and the prediction of aerodynamic trends. In practice, capturing the correct behaviour of the phenomena, such as the variation of lift and moments as a function of the angle of attack, is more important than achieving complete agreement in absolute values. In this context, CFD and experiments are

treated as complementary: experimental measurements provide a reference point and validation, while numerical simulations serve as a tool for an in-depth flow analysis and the investigation of variants that are difficult to test experimentally.



Figure 32. A view of the constructed XGyro prototype.

The numerical calculations and wind tunnel tests presented in this study were application-oriented and directly supported the design development process. Based on the obtained aerodynamic characteristics and their experimental validation, it was possible to design and construct an actual prototype of the hybrid aerial vehicle. The photographs in Fig. 32 illustrate the final outcome of the work, showcasing the constructed vehicle, which fully reflects the design assumptions and conclusions derived from the analyses. This highlights the practical usefulness of conducting parallel numerical and experimental studies, which synergistically contributed to

reducing design risk and increasing the efficiency of the development process. Flight tests, planned as the next stage of the research, constitute a natural extension of the presented analyses and will become the subject of a separate publication.

5. Conclusions

Based on the conducted research, the main objective was achieved by obtaining reliable information on the aerodynamic properties of the analysed fuselage–empennage airframe. Considering the assumed high maneuverability of this aircraft, obtaining such data during the design process is of critical importance. The article presents the results of numerical analyses of the airflow around the analysed fuselage–empennage airframe of the XGyro, with a particular emphasis on the effects of the angle of attack and sideslip angle on its aerodynamic characteristics. Wind tunnel experiments were also conducted to validate the developed models.

The analysis of the aerodynamic characteristics of the studied object (XGyro fuselage with empennage), based on CFD calculations, enabled the formulation of the following conclusions:

- The aerodynamic drag coefficient (C_x) exhibits classical behaviour, with minimum values observed at low angles of attack ($\alpha \approx 0-5^\circ$), corresponding to the expected range of level flight. An increase in the sideslip angle β leads to a systematic increase in the drag coefficient C_x .
- The side force coefficient (C_Y) is close to zero at $\beta = 0^\circ$, confirming the geometric symmetry of the research object. An increase in β results in the emergence of positive C_Y values, which grow with α , reflecting the effects of asymmetric flow.
- The lift coefficient (C_Z) exhibits a linear dependence on the angle of attack within the operational range. Negative values are observed at negative angles of attack α , whereas a predictable increase in lift occurs for positive α . The influence of the sideslip angle β on the C_Z characteristics is limited and does not disrupt their monotonic behaviour.
- At $\beta=0^\circ$, the rolling-moment coefficient CM_X remained close to zero, confirming the expected aerodynamic symmetry of the model. At non-zero sideslip angles, the negative derivative $d_{CM_X}/d\beta$, evaluated under the adopted

sign convention, indicated a restoring rolling response of the analysed airframe.

- The pitching moment coefficient (C_{MY}) exhibits behaviour which is typical of aerodynamically stable configurations. For negative α , the values are positive (indicating a nose-up tendency), whereas for positive α , they are negative (indicating a nose-down tendency).
- The yawing moment coefficient (C_{MZ}) remains close to zero at $\beta = 0^\circ$, and assumes small positive values as the sideslip angle increases. The scale of differences is limited (up to approximately 0.0024), which indicates the absence of excessive tendencies for spontaneous fuselage yawing and confirms the correctness of directional stability.

In summary, all the analyzed aerodynamic coefficients obtained using the CFD method exhibit classical characteristics consistent with expectations. The obtained results indicate that the adopted fuselage geometry of the XGyro, together with its empennage, ensures favourable aerodynamic characteristics as well as maintained longitudinal, lateral, and directional stability across the full range of analyzed angles of attack and sideslip.

The experimental investigations conducted in the wind tunnel enabled a comprehensive assessment of the aerodynamic characteristics of the analysed airframe model within the range of angles of attack from -20° to $+20^\circ$ and sideslip angles from 0° to 20° . The analysis of force and moment coefficients revealed consistency in trends with the CFD numerical results, while also highlighting certain quantitative differences arising from the nature of the experiment and limitations of the measurement methodology. The drag coefficient C_x reached its minimum values in the range of $\alpha \approx 0-5^\circ$ and increased as the angle of attack moved away from this range toward either negative or positive values. At a given angle of attack, an increase in the sideslip angle generally resulted in higher C_x values. The side force coefficient C_Y exhibits the expected asymmetry as a function of sideslip angle, with its values increasing systematically with β , indicating a correct representation of lateral aerodynamic stability. The results for the lift coefficient C_Z are particularly significant, as it exhibits an approximately linear increase with the angle of attack, attaining its maximum values in the range of $\alpha = 15^\circ-20^\circ$. Thus, the maximum aerodynamic efficiency C_Z/C_x was also

determined, reaching 5.2 for $\beta = 0^\circ$ and gradually decreasing to 2.65 at $\beta = 20^\circ$. These results indicate that the analysed airframe achieves its most favourable aerodynamic characteristics at small sideslip angles, which is consistent with theoretical predictions and confirms the validity of the applied design solutions.

The comparison of CFD and wind tunnel results for the selected angle $\beta = 0^\circ$ points to very good qualitative and quantitative agreement. All aerodynamic coefficients exhibit the same trends and similar absolute values. The differences fall within an acceptable range and are primarily attributed to the limitations of the numerical method (mesh, turbulence model) as well as experimental inaccuracies. The best agreement was observed for C_X and C_Z , while slightly larger discrepancies were noted in the moment coefficients (C_{MX} , C_{MY} , C_{MZ}), which is typical due to the higher sensitivity of these quantities to local flow behaviour.

It should be noted that the present analysis does not include the main rotor and therefore the results apply only to the non-

rotor airframe and do not capture rotor–fuselage interaction effects. In future research, both the numerical and experimental analyses are planned to be further extended. In particular, additional CFD simulations are planned using more advanced turbulence models, as well as nonlinear analyses over a wider range of angles of attack and sideslip, including stall conditions. From an experimental standpoint, future wind tunnel tests are planned with a model equipped with a main rotor, enabling the assessment of rotor–airframe interaction effects and their influence on the overall aerodynamic behaviour of the system. In addition, flight testing of the actual prototype is planned as a future stage to assess the flight characteristics of the complete configuration. The corresponding test procedures and results will be presented in a separate publication. The present work establishes the aerodynamic feasibility at the airframe level for the tested configuration, while a full-configuration assessment requires further studies including the main rotor and rotor–airframe interaction effects.

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