Numerical analysis of the airflow around the Gyro-One autogyro

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Abstract. The paper presents the results of numerical tests of the aerodynamics of the Gyro-One unmanned autogyro model. The geometry of the research object was developed using reverse engineering and CAD software. The created solid model of the aircraft was entered into the Ansys Meshing to generate a mesh. The boundary conditions and turbulence model were defined with Ansys Fluent software. The calculated parameters include the aerodynamic forces and the pitching moment generated on individual elements calculated with the CFD method for the selected values of the angle of attack, the velocity and pressure distributions in the plane of symmetry, and the pressure distribution on the aircraft surface for the defined measurement points. The obtained results made it possible to analyse the flow around the research object and become an introduction to further research into a hybrid multi-rotor aircraft based on the autogyro design.

1. Introduction
Aerodynamic properties of gyroplanes have been the subject of many research works [1-4]. Numerical modelling is increasingly popular in aerodynamic analyses. The computational fluid dynamics (CFD) method for aircraft designs allows to determine their aerodynamic properties by analysing external forces acting on their surface and their coefficients [5]. This kind of simulation software is also capable of creating maps of velocity and pressure distribution on specific surfaces, visualising the airflow around the tested object, and analysing the aerodynamic interaction of particular elements of the aircraft, e.g. its rotor with its fuselage [6]. The main advantage of this method is that it can solve a given problem without complex experiments. Unlike experimental studies, numerical modelling allows for validating design assumptions at the design stage and avoiding a costly preparation of a real research object to conduct experiments. Usually, these methods are cheaper and make it possible to obtain data that are difficult to obtain in experimental studies [7-8]. Numerical models, however, can be compared with results of experimental tests in the wind tunnel [9-10].

The CFD method can also be useful in analysing aerodynamics of helicopters [11-14]. The aerodynamic characteristics of the forces and moments acting on the helicopter fuselage were determined in [15]. They were also developed in simulations of the airflow through the main rotor in flight conditions with forward speed. The airflow around the helicopter was also calculated in [16]. The research focused on the impact of individual helicopter elements on aerodynamic characteristics.
and showed that additional external elements such as cameras, wings, pylons, armament, etc. have a significant impact on aerodynamic properties of the aircraft.

The aim of this work is to conduct a preliminary analysis of the aerodynamics of the unmanned autogyro model. The first stage of the simulation studies focused on creating a geometric model of the research object with CAD software. Next, the geometric model was discretised and transformed into a set of finite elements (mesh). The mesh was made as non-structural with tetrahedral elements because the shape of the aircraft fuselage was complex. The calculations were performed as three-dimensional, steady, incompressible, using a defined turbulent flow model. The obtained research results will be used in further research on a hybrid multi-rotor aircraft based on the autogyro design.

2. Research object and methodology

The research object is a model of the Gyro-One unmanned autogyro (Figure 1). The tested aircraft is a low-profile gyroplane, which means that its centre of gravity is below the line of action of propeller thrust (in the pusher case). At the end of the tail boom, there is a stabilizer, and in the rear upper part of the fuselage, there is an electric engine with a push propeller and a mast with a two-bladed main rotor. The gyrocopter has a three-wheeled landing gear attached to the front of the fuselage and the supporting frame. The main rotor is equipped with a pre-rotation system consisting of an electric motor and a toothed gear. The electric motor connected to the two-bladed propeller generates horizontal thrust. The basic technical parameters of the tested aircraft are presented in Table 1.

Figure 1. Gyro-One autogyro.

Table 1. Basic technical data of the research object.

| Parameter                        | Description          |
|----------------------------------|----------------------|
| Length x height                  | 1050 mm x 510 mm     |
| MTOW                             | 4 kg                 |
| Main rotor diameter              | 1800 mm              |
| Prerotator engine                | ROXXY BL-Outrunner   |
|                                  | 2834/12              |
| Main engine                      | ROXXY BL-Outrunner   |
|                                  | 3548/05              |
| Push propeller (length x pitch)  | 11 x 7”              |
| Battery                          | LiPo 3S 5000 mAh     |
Reverse engineering was used to create a solid model of the tested aircraft. The surface of the fuselage was scanned with a ZScanner 700 handheld scanner. The process of preparing the surface of the object required markers to automatically connect the individual parts of the scan so that the scanner could recognise the surface in relation to the previous position after changing the scanning area (moving the device in relation to the scanned object). The gyroplane fuselage surface was digitised with a scanning accuracy of 1 mm (Figure 2). This scan was used to create its surface model in Catia v5 using the Digitized Shape Editor and Generative Shape Design modules. The fuselage surface model was later converted to its solid model.

![Figure 2. Scanned surface of the fuselage with markers.](image)

The created solid model of the entire gyroplane had neither a rotor head, blades and an engine nor internal components of the aircraft such as batteries, transmission systems, wires, etc. because this analysis focused on the airflow around the research object. The fasteners and holes were removed before the model was numerically calculated so the mesh generation process was improved and the obtained results of numerical calculations were not significantly affected.

Figure 3 shows the centre of gravity of the aircraft (point CG) and the corresponding clockwise coordinate system. It is assumed that a positive moment causes a clockwise rotation around the axis of the coordinate system, looking from the original side towards the positive sign of the axis. The angle of attack $\alpha$ is calculated with a positive sign clockwise. The centre of the coordinate system is at the centre of gravity of the gyroplane. The tests were carried out for several defined values of the angle of attack from $\alpha = -25^\circ$ to $\alpha = 25^\circ$ every $5^\circ$.

![Figure 3. Model of the tested gyroplane with the adopted coordinate system.](image)
This geometric model was imported into the ANSYS Design Modeler module. The first step in adjusting the geometry was to reduce the number of model faces to faster obtain a higher quality mesh. Then, a large number of features was reduced by joining the smaller surfaces and creating the larger ones with the Merge tool. The geometry was prepared with the Repair option and functions such as Hard Edges, Edges, Seams, Holes, Silvers, Spikes, Faces.

After creating the final geometry in the Ansys Meshing module, a mesh created by the Tetrahedrons method with the Patch Conforming algorithm was generated for the test object (Figure 4). On the fuselage surface, an Inflation boundary layer of 16 layers was defined with the Smooth Transition option. The maximum value of the Skewness factor was increased to 0.97. The thickness of the boundary layer was specified based on the type of flow determined from Reynolds numbers. The total mesh consisted of 10,797,005 elements and 3,763,220 nodes. The values of forces and moments on individual elements of the aircraft were obtained by sectioning its body into a fuselage, support frame, and stabilizer (Figure 5). The generated mesh consisted of tetrahedral elements with a boundary layer.

![Figure 4. Generated mesh of the gyroplane model (left) and a cross-section of a discrete computational domain (right).](image)

![Figure 5. Sections of the research object.](image)

The numerical tests were performed using the computational solver in the Ansys Fluent software. Its parameters are presented in Table 2. Based on the works [8, 17, 18], the k-ω SST turbulence model was used. The kinetic energy of the turbulence k near the wall is equal to zero. The rate of dissipation of the turbulence kinetic energy ω in the vicinity of the wall tends to infinity. Its value can be determined, however, it will have a very high value. Based on the literature and own experience, the k-ε model was not applied because it does not work well for the modelling of flow near the wall and does not reflect the phenomena occurring in the boundary layer (occurrence of shear stresses, etc.). The k-ε model gives...
reliable results for a slow flow (away from the boundary layer) where a turbulence occurs in the entire area.

The measuring area the tested object was placed on is a cuboid of $4 \times 4 \times 8 \text{ m}$ with the defined velocity inlet and pressure condition on the outlet surface (pressure outlet) [19]. The calculations were based on steady- and pressure-type analyses. Air was defined as the working gas and the flow was assumed as incompressible. The incompressible ideal gas function was chosen to define the properties. This is a proper approach if the model includes a flow with velocities lower than 0.3 Ma [11, 15, 20].

| Table 2. Defined solver parameters in Ansys Flent software. |
|-----------------------------------------------|
| **Parameter** | **Description** |
| Type | Pressure-based |
| Time | Steady |
| Viscous | k-$\omega$ (2-eqn) SST |
| Fluid materials | Air |
| Density | Incompressible ideal gas |
| Viscosity | Constant |
| Velocity [m/s] | 15 |
| Inlet | Turbulent intensity [%] | 1 |
| Turbulent length scale [m] | 0.28 |
| Pressure-outlet | Gauge pressure 0 Pa |
| Outlet | Turbulent intensity [%] | 1 |
| Turbulent length scale [m] | 0.28 |

3. Results and discussion
The parameters obtained in the calculations include the pressure distribution on the surface of the test object and in the plane of symmetry as well as the velocity distribution in the plane of symmetry of the test object for the extreme values of the angle of attack $\alpha$, i.e. $-25^\circ$, $0^\circ$, and $25^\circ$. The obtained results are shown in Figure 6 - Figure 8.

**Figure 6.** Pressure (left) and velocity (right) distribution on the gyrocopter surface and in the symmetry plane of the test object for $\alpha = -25^\circ$. 
The highest positive pressure occurred for the zero angle of attack (175 Pa). In all cases, a significant increase in pressure occurred at the nose of the fuselage and the mast. For the extreme angles of attack of -25° and 25°, its values were respectively 130 Pa and 133 Pa. The lowest negative pressure was for the zero angle of attack (-296 Pa) and the highest one for $\alpha = 25^\circ$. They were equal to -296 Pa and -435 Pa, respectively. For the extreme positive angle of attack below the connection of the support frame with the stabilizer, there was an area of increased pressure.

![Image](image1.png)

**Figure 7.** Pressure (left) and velocity (right) distribution on the gyrocopter surface and in the symmetry plane of the test object for $\alpha = 0^\circ$.

![Image](image2.png)

**Figure 8.** Pressure (left) and velocity (right) distribution on the gyrocopter surface and in the symmetry plane of the test object for $\alpha = 25^\circ$.

While analysing the velocity distribution for the angle of -25°, an area of zero velocity was observed between the fuselage and the stabilizer. The highest velocity, i.e. 22.5 m/s occurred at the upper edge of the mast. The increase in the angle of attack to 0° caused this area to move up towards the wake of the mast. The further increase in the value of the angle of attack resulted in a significant change in the velocity distribution behind the fuselage and mast. Several smaller areas of reduced velocity were
observed. The highest velocities for the 0° and 25° angles occurred at the lower edge of the fuselage (19.1 m/s and 18.5 m/s, respectively).

Drag, lift, and pitching moment on individual elements of the aircraft were also calculated in the simulation and then their aerodynamic coefficients were calculated from formulas (1) and (2):

\[ C_i = \frac{P_i}{0.5 \rho v^2 \pi R^2} \]  
\[ C_{My} = \frac{M_y}{0.5 \rho v^2 \pi R^3} \]

where:
\[ C_i \] – the aerodynamic force coefficient [-], drag component \( x \) and lift component \( z \), respectively.
\[ C_{My} \] – the aerodynamic pitching moment coefficient [-],
\[ P_i \] – component of the aerodynamic force [N],
\[ i \] – index corresponding to the spatial component \( x \) and \( z \), respectively,
\[ R \] – main rotor radius equal to 0.9 m,
\[ \rho \] – air density equal to 1.225 kg/m\(^3\) (for temperature 288.15 K),
\[ v \] – air velocity equal to 15 m/s.

Table 3 presents the total values of the aerodynamic forces, the pitching moment, and their aerodynamic coefficients for the analysed range of \( \alpha \). These values were obtained for the fuselage, stabiliser, and supporting frame. Figure 9 and Figure 10 show the characteristics of the calculated coefficients with the sections of the research object.

| \( \alpha \) \[°\] | \( P_x \) [N] | \( P_z \) [N] | \( M_y \) [Nm] | \( C_i \) [-] | \( C_z \) [-] | \( C_{My} \) [-] |
|---|---|---|---|---|---|---|
| -25 | 6.280 | -7.070 | 6.253 | 0.018 | -0.020 | 0.020 |
| -20 | 6.052 | -6.723 | 5.666 | 0.017 | -0.019 | 0.018 |
| -15 | 5.784 | -7.293 | 6.000 | 0.017 | -0.021 | 0.019 |
| -10 | 5.116 | -6.208 | 4.928 | 0.015 | -0.018 | 0.016 |
| -5 | 4.452 | -3.680 | 2.731 | 0.013 | -0.011 | 0.009 |
| 0 | 4.031 | -0.974 | 0.395 | 0.011 | -0.003 | 0.001 |
| 5 | 3.917 | 1.930 | -2.033 | 0.011 | 0.006 | -0.006 |
| 10 | 4.241 | 4.345 | -4.111 | 0.012 | 0.012 | -0.013 |
| 15 | 4.943 | 6.123 | -5.670 | 0.014 | 0.017 | -0.018 |
| 20 | 5.724 | 7.190 | -6.687 | 0.016 | 0.021 | -0.021 |
| 25 | 6.784 | 7.728 | -7.464 | 0.019 | 0.022 | -0.024 |

The drag force coefficient \( C_x \) for the zero angle of attack had its lowest value equal to 0.011. In relation to other aircraft (including manned), this value is quite high. For example, the drag coefficient of the Fusioncopter gyroplane according to [17] is equal to 0.007. Even helicopter fuselages have slightly lower drag coefficients, i.e. around 0.0075. This value may be higher if the rotorcraft has additional external equipment such as pylons, fuel tanks, armament, or cameras [16]. The increase of the angle of attack to 25° resulted in an increase of the coefficient to 0.019. For large negative values of the angle of attack, the curve changed its trend, and for \( \alpha = -25^\circ \) the coefficient was equal to 0.018.

The highest value of the drag force coefficient was 0.022 for the angle of attack equal to 25°. The smallest values, i.e. ranging from 0.019 to 0.021 occurred for the large negative angles of attack from -15° to -25°. In general, as the angle of attack increased, the value of the coefficient increased, too. For the angles of attack from -10° to 10°, the trend was approximately linear.
Figure 9. Coefficient of the drag force of the tested object (left) and the coefficient of the lift force (right) as a function of $\alpha$.

Figure 10. Pitching moment coefficient of the tested object as a function of $\alpha$.

The characteristic of the pitching moment coefficient (Figure 10) is an approximately decreasing linear function in the range from $-15^\circ$ to $25^\circ$. This means that the tested aircraft maintains stability in this range of angles. For large negative angles of attack, the characteristic changed its shape, which means deterioration of stability. The zero value of the coefficient occurred for about $1^\circ$. Thus, to conduct horizontal flight, it is necessary to slightly tilt the aircraft in relation to the wind direction. The highest absolute value of the coefficient equal to $-0.024$ occurred for $\alpha = 25^\circ$.

4. Conclusions
The paper presents the results of numerical calculations of the aerodynamics of the Gyro-One unmanned autogyro. The gyroplane model was created using reverse engineering and CAD software. As a result of the calculations, the forces and aerodynamic moment generated on selected elements of the aircraft for the defined values of the angle of attack were obtained.
By analysing the pressure distribution on the external surfaces of the studied geometry, it is possible to locate places with high-pressure values. These include a mast made of a square-shaped profile (its flat wall slows down the flow and generates a lot of drag) and supporting frame components. The fuselage itself, as it constitutes the largest percentage of the total drag force, can also be optimised to reduce the drag force. The high value of the drag force is a consequence of the relatively large surface area which is the projection of the fuselage onto a plane perpendicular to the airflow direction.

Other parameters like velocity and pressure distributions in the plane of symmetry as well as the pressure distribution on the aircraft surface for the defined measurement points were also determined. The negative pressure zone behind the fuselage caused by its shape change is noticeable. The significant pressure drop and velocity increase occurred at the edge of the lower fuselage. The conducted analysis made it possible to quantify the imperfections of the shape of the research object. The aerodynamic characteristics of the Gyro-One autogyro obtained from the numerical calculations become a comparative basis for the planned versions of the hybrid unmanned aerial vehicle. The analysed gyroplane is a tested object that performed flights, so it can be a reference model for newly-designed flying units.

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