Numerical calculations of the autorotating rotor under transient conditions

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Abstract. It is necessary to evaluate the performance of the main rotor in design stages of a
rotorcraft to obtain the assumed lift force and low aerodynamic drag. This paper presents the
CFD numerical analysis of the autorotating rotor under transient conditions. Auto-rotation is
particularly important in the case of gyrocopters, while in the case of helicopters it is related to
flight safety. The calculations allowed us to obtain aerodynamic forces and torque as a function
of rotor azimuth for individual rotor blades. The analysis was performed for a rotor tilted by 15
degrees toward the airflow direction. A geometric model was created for the calculations and
then a computational model was created in Ansys Fluent software. The k-ω SST model was
adopted as the turbulence model which considers the turbulence kinetic energy and its unit dis-
sipation. The obtained results are presented in a rotor and flow coordinate system.

1. Introduction
The autorotation phenomenon is crucial to the operation of gyro-copters. It allows the rotor to rotate
spontaneously and maintain a constant speed due to the interaction of the flowing air with blades [1].
On the other hand, the main rotor in a helicopter allows the transition to autorotation flight, which can
improve the safety of the aircraft [2]. For both cases, it is necessary to analyze dynamics of rotor systems
to evaluate aerodynamic performance. According to the rotary-wing aircraft theory, one of the
fundamental dynamic problems of the rotor is asymmetry of flow and asymmetry of blade loads [3].
The aerodynamic characteristics of the airfoil under steady-state conditions is incorrect due to rotational
motion of the blade and dynamics of flow phenomena. For this reason, it is particularly important to
analyze lift and drag as a function of rotor blade azimuth because the rotor must provide a sufficient
force to realize different flight modes and overcome aerodynamic drag. The main rotor should also be
well balanced to eliminate vibrations [4] and instabilities due to the nonlinear nature of operation [5].

Rotor operation over time can be analyzed by mathematical modeling, including simulation based
on computational fluid dynamics (CFD) [6-8] as well as by experiments on a test stand [9] or in a wind
tunnel [10,11]. The CFD method is also widely used in the analysis of steady-state aerodynamic
interactions [12] and rotor wake geometry [13,14]. Many numerical computational works investigate
streamlines around the fuselage together with the empennage of flying objects, including gyrocopters
without any rotating components such as propellers or main rotors. This simplified approach allows for
easier calculations and is often used for investigation of basic aerodynamic characteristics or stability [15-18] at an early stage of aircraft designing.

A mathematical modeling of the rotor is often conducted using the blade element theory (BEM) [19,20] and blade element momentum theory (BEMT) [21,22] which is a modification of the latter. Other methods such as actuator disks [23], a virtual blade model [24] or the Timoshenko beam theory are also used to account for aeroelastic effects [25]. An interesting study of transient loads and blade deformations on coaxial rotor systems using the coupled method (computational fluid dynamics and computational structural dynamics) is presented in [26].

The objective of this study was to analyze the aerodynamic performance of a main rotor dedicated to a light unmanned aerial vehicle. For this purpose, a geometrical and computational model of the research object was developed and presented in Section 2. The calculations were performed using computational fluid dynamics under transient conditions to evaluate the aerodynamic properties of the rotor as a function of time. The calculation results and their analysis are presented in Section 3 and the conclusions were drawn in the last section.

2. Research object and methodology
The research object was a two-bladed rotor of a designed unmanned aerial vehicle weighing up to 5 kg (figure 1). This aircraft will be a combination of a gyrocopter and a multirotor. Such a solution will allow for a hover and a vertical take-off while maintaining classic gyrocopter functionality.

The main rotor is fully articulated and has no vertical joint. A horizontal joint is common for both blades and connects the head rotor to the shaft. The rotor is controlled by the head and there is no possibility of changing the collective pitch of the blades during flight. The whole structure is mounted on a metal mast attached to the fuselage structure. The blades of the NACA 8-H-12 profile have a length of 880 mm and a width of 72 mm. This is a non-symmetrical profile used in gyrocopters. The paper [27] presents a numerical load analysis of a blade structure using this profile. The final version of the blades will be made of drawn aluminum and will be anodized and finely balanced.

![Figure 1. Geometrical model of the designed aircraft (left) and the tested rotor (right).](image)

Preprocessing was started by creating a geometric model of the rotor in SolidWorks software (figure 1). The shape was simplified by eliminating unnecessary edges, rounds, holes, etc. This reduced potential errors in the mesh generation and wall layer calculations.

The research object was placed in a rectangular computational domain (figure 2). The rotor was surrounded by a flat cylinder. The domain walls were spaced 3000 mm from the rotor axis. The wall perpendicular to the X-axis was defined as an inlet and the one opposite to it as an outlet. The other surfaces were defined as a wall and a bottom.

A computational grid was then generated for the created domain (figure 2). The tetragonal mesh was concentrated around the cylinder surrounding the test object using edge and face sizing functions. The number of mesh elements was 12522509 with a max skewness of 0.86.

The turbulence model was defined as k-ω SST in the solver of the software. The calculations were performed as transient and were based on pressure values. The principal stresses in the flow were
included in the turbulence model. The calculations were performed with the assumed turbulent intensity and turbulent viscosity ratio whose values were 1% and 5, respectively. Air (ideal gas) of a temperature of 288 K (15°C) and a viscosity of $1.7894 \cdot 10^{-5}$ kg/(ms) was assumed as fluid. The operating pressure was 101325 Pa. The airflow velocity was equal to 20 m/s.

Initializing the created model and checking the convergence of subsequent iterations were followed by a series of calculations for the defined rotor speeds.

Figure 2. The computational domain with the research object (left) and the created computational mesh (right).

3. Results and analysis

Numerical analysis of an autorotating main rotor for a model of a gyrocopter with a take-off weight of up to 5 kg was performed for an angle of attack $\alpha$ equal to 15 degrees. This angle was measured in the longitudinal plane of symmetry of the domain in relation to the direction of airflow. The calculations were performed to obtain lift, drag and torque as a function of rotor azimuth for two selected constant values of rotor speed, i.e. 400 and 600 rpm. The obtained values were presented in the rotor coordinate system (RCS) for each rotor blade, and then the total and average values of the respective quantities were calculated. Blade 1 at the beginning of the calculation was the advancing blade, while blade 2 was the retreating one. The results are presented for three consecutive cycles (full rotor revolutions).

Figure 3. Lift force for rotor speeds of 400 rpm (left) and 600 rpm (right) as a function of rotor azimuth in the rotor coordinate system.

The first of the considered parameters was the lift force as a function of rotor azimuth (figure 3). For a speed of 400 rpm, the force on the single blade varied from 6 to 39 N. The shape of the curve as a
function of rotor azimuth was approximately sinusoidal. Each blade produced a thrust force of 18 to 23 N on average. To evaluate the total force generated by the rotor, the data series for each blade were summed. The total force varied from 35 to 45 N. Increasing the rotor speed to 600 rpm resulted in a significant increase in the values of the parameters considered. The total force increased by more than 50% to 66-77 N. Similarly, the values of forces on individual blades and the value of the average force increased. Moreover, an increase in the amplitude of the force on the single blade was observed for higher rotor speed.

Then, the drag force as a function of rotor azimuth was analyzed (figure 4). The drag force on the single blade for a rotor speed of 400 rpm varied from -0.9 to 1.7 N. The shape of the curve was approximately sinusoidal. However, an additional local extreme was observed with a value of about -0.1 N, which indicates the presence of an additional harmonic in the obtained drag force waveform. The average value of the force per blade varied between -0.5 and 0.8 N. The total force has a sinusoidal trend and its value ranged from -1.0 to 1.5 N. An increase in rotor speed to 600 rpm resulted in a decrease in the values of all the parameters considered. The value of the total force was negative for almost the entire azimuth (from -2.1 to 0.1 N) and had a sinusoidal trend. The mean value varied from -1.0 to 0 N. The force on the single blade varied from -1.4 to 1.0 N. In addition, a second additional harmonic was observed in the force waveform.

Another parameter considered was torque as a function of rotor azimuth (figure 5). For smaller values of rotor speed, the torque on the single blade varied from 0.1 to 0.9 Nm. Its trend was similar to sinusoidal. As in the case of the drag force, there was an additional harmonic with a maximum value of 0.5 Nm. The average value of the force per blade varied from 0.4 to 0.7 Nm, while the total value varied from 0.7 to 1.4 Nm. An increase in rotor speed (600 rpm) resulted in a slight decrease in the total torque (0.5-1.3 Nm) and its average value (0.3-0.6 Nm). The torque for the single blade varied from -0.3 to 0.9 Nm and took negative values for a certain range of azimuth. Moreover, its shape changed significantly. The torque amplitude increased by about 50%. An additional local extreme took a higher value (0.6 Nm) and occurred behind the global maximum. In the case of lower rotor speed (400 rpm), the local extremum occurred behind the global minimum.
Figure 5. Torque for rotor speeds of 400 rpm (left) and 600 rpm (right) as a function of rotor azimuth in the rotor coordinate system.

Next, the lift force and drag force values were converted to the flow coordinate system (figure 6). Analysis of the values in this system allows evaluating the rotor performance in terms of suitability for the designed UAV. As in the case of the graphs for the rotor coordinate system, the values of total force and mean force for the analyzed rotational speeds are presented. The values also differ significantly because the components of the lift and drag forces were projected onto the axes of the coordinate system associated with the flow. This system was rotated with respect to the RCS by 15 angular degrees in relation to the direction of airflow in the longitudinal symmetry plane of the computational domain.

The resulting total lift force for a rotor speed of 400 rpm varied from 34 to 45 N and was more than 40% less compared to a speed of 600 rpm (64 to 75 N, respectively). The average value of the force generated by a single blade for the considered speeds was 17-23 N and 32-37 N, respectively. The total drag force for a speed of 400 rpm was 8-13 N. An increase in speed to 600 rpm resulted in a significant increase in force, i.e. 15-20 N. The average force values per blade were 4-7 N and 8-10 N, respectively.

Figure 6. Lift force (left) and drag force (right) for rotor speeds of 400 rpm and 600 rpm as a function of rotor azimuth in the flow coordinate system.

4. Conclusions
This paper presents the results of the numerical calculations of a main rotor designed for a light unmanned aerial vehicle.

The characteristics of lift, drag and aerodynamic torque as a function of rotor azimuth for the selected rotor speeds were obtained from the performed simulations and presented in the defined coordinate systems. The calculations showed a significant influence of rotor speed on the values of the considered parameters. An increase in rotor speed increased the lift and drag forces. In the case of torque, an increase
in rotor speed resulted in a slight decrease in its total and average values. This indicates that the considered rotor speed \( n = 600 \text{ rpm} \) is not the maximum rotor speed for this rotor and certainly the obtained values of the lift force are not maximum. The maximum value of the lift force in the gyrocopter rotor will be reached at the maximum speed corresponding to the balance of the torque driving the rotor blades from the airflow and the torque from the aerodynamic and mechanical drag acting on the rotor. For the drag force and torque curves for the single blade, the observed additional harmonics changed the sinusoidal nature of the function over time. For higher rotational speed, a total drag force in the range of 64-75 N (for the flow coordinate system) was obtained, which means that the analyzed rotor can provide sufficient thrust for the designed aircraft of a weight up to 5 kg.

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