CFD investigation of the aerodynamic characteristics of the autogyro with a double tail stabilizer

Z Czyż¹, P Karpiński² and K Skiba²
¹ Aeronautics Faculty, Military University of Aviation, 35 Dywizjonu 303 St., 08-521 Dęblin, Poland
² Department of Thermodynamics, Fluid Mechanics and Aviation Propulsion Systems, Faculty of Mechanical Engineering, Lublin University of Technology, 36 Nadbystrzycka St., 20-618 Lublin, Poland
z.czyz@law.mil.pl

Abstract. Drag, lift and pitching moment were calculated for the tested aircraft sectioned into the fuselage and stabilizer. The analysis also covered the pressure distribution on the surface of this aircraft and on its symmetry plane. The values of the analysed forces and moments on individual parts of the stabilizer for the defined angles of attack were also obtained. The conducted analysis is a preliminary aerodynamic study of a new type of aircraft which is a combination of a gyroplane and a multi-rotor. The obtained results allow the assessment of the aerodynamic performance of the aircraft with a double tail stabilizer and constitute the basis for further optimisation studies.

1. Introduction
Numerical fluid dynamics is a basic tool for aircraft designers [1]. Determining aerodynamic characteristics based on the already existing models makes it possible to assess aircraft aerodynamic performance [2-3]. Conducting numerical simulations during the development of new constructions allows for the development of aircraft with an increased aerodynamic performance at a relatively low cost compared to experimental tests [4]. This applies to both aerodynamics of the aircraft fuselage and its components [5-7]. A popular tool used in aerodynamic calculations is Ansys Fluent [8-9], whereas CAD software is used for designing and constructing [10].

Gyrocopters are interesting aircraft which are gaining popularity thanks to the development of small civil aviation [11-12]. Apart from introducing new designs of gyrocopters to the market, gyrocopters are improved by research [13-14]. The paper [15] presents the results of research of aerodynamic forces and moments acting on the modern gyroplane structure capable of short take-off, or the so-called jump-start. The authors of the work [16] present the results of research on aerodynamic interference occurring during the flight of a multi-rotor hybrid unmanned aerial vehicle. The object of the research is an aircraft that combines the features of a gyroplane and multi-rotor. Thanks to this aircraft model, an unmanned system capable of vertical take-off and landing was created, which was unavailable for gyroplanes themselves. The tests were carried out in a continuous-flow low-speed wind tunnel with an open measuring space, 1.5 m in diameter and 2.0 m long. The research defined the influence of additional power units on the lift force generated by the main rotor of the gyroplane.

A characteristic feature of the gyroplanes is the use of autorotation, which significantly reduces the power demand in horizontal flight [17-18]. Combining the capabilities of the gyrocopter with multi-
rotor aircraft allows for the development of a design that combines the advantages of various aircraft [19-20] but also requires a series of numerical tests [21]. One of the research stages is the calculation of the aerodynamic characteristics of the gyroplane model with a double tail stabilizer presented in this paper.

In this work, the drag force, lift force and pitching moment were analysed for the fuselage and stabilizer. The analysis also focused on the pressure distribution on the aircraft surface and on the plane of symmetry, and the selected forces and pitching moment generated on the selected parts of the stabilizer for different values of the angle of attack were compared.

2. Research object and methodology

The object of the research was a gyroplane model with a double tail stabilizer based on the NACA 0012 profile. The aircraft fuselage was created in the Catia v5 software (Figure 1). Its dimensions are 1071 × 719 × 427 mm (length × width × height). Ansys Fluent software was used to perform numerical calculations. To carry out preliminary aerodynamic tests of the research object, its model was simplified by eliminating its main rotor, additional horizontal rotors and landing gear. Generally, the test object was assumed to operate with a rotor diameter of 1.9 m.

![Figure 1. Model of the tested aircraft (left) and the generated mesh on its surface (right).](image)

In the Mesh module, using the Patch Conforming/Sweeping mesh generation method, a computational mesh consisting of 2,312,534 elements was created. In order to improve its overall quality, Edge Sizing and Face Sizing were used on the critical edges and surfaces of the research object. In addition, with the Inflation option, the mesh refinement in the boundary layer was applied. The mesh generated for the tested aircraft is shown in Figure 1.

The k-ω SST turbulence model was adopted, which works well in the analysis of the aerodynamics of the entire aircraft. This model takes into account the turbulence kinetic energy k and the specific rate of dissipation ω. The turbulence intensity of 1% and the turbulence length scale of 0.28 m were assumed.

The research model was placed in the computational domain with dimensions of 6000 × 4000 × 4000 mm (length × height × width). One wall has a velocity inlet and a pressure outlet defined on the opposite wall. The remaining walls and the surface of the test object were defined as a wall. In the case of an aircraft, the fuselage and the left and right parts of the stabilizer are defined as separate elements. The airflow velocity was set at 20 m/s. The numerical tests of the aircraft aerodynamics were carried out for several values of the angle of attack from -20° to 20°, every 5°. The position of the aircraft relative to the incoming air was changed using the Body Operation in the Design Modeller module.

3. Results and discussion

Drag, lift and pitching moment for the fuselage and stabilizers of the research object were calculated. Figure 2 shows the drag force versus the angle of attack for the test object. The force on the fuselage changed slightly, from 3.5 to 7.2 N. For the extreme positive value of the angle of attack (20°), there
was a lower drag force value compared to the angle of attack equal to -20° (5.5 N and 7.2 N, respectively). The opposite relationship occurred for the stabilizers. The obtained curve for the left and right stabilizer coincide, which proves symmetrical flow around the test object. The total force on the stabilizers changed from 1.1 to 7.8 N. The lowest value was observed for the zero angle of attack. It is worth noting that for the angles of attack equal to -20° and 20°, the force on the stabilizer was higher than on the fuselage. This means that at high values of the angle of attack, the stabilizer plays an important role in generating the drag force. The total force for the test object was similar to the force on the stabilizer. Its lowest value occurred for the angle of attack equal to 0°, and the highest values were observed for the extreme angles of attack equal to -20° and 20° (14.7 N and 13.4 N, respectively). This is in line with our expectations because as the pitch increases, the face area affected by the airflow increases.

Figure 2 also shows the lift force for the defined angles of attack. The obtained curves have a similar shape and differ essentially in their absolute values. The force components had negative values for the negative angle of attack and vice versa. For small values of the angle of attack, their trend was linear. For all considered components, the zero value of the lift force occurred approximately for the zero angle of attack. The lift forces for the left and right stabilizer were the same, and this trend was similar to the force on the fuselage. For the extreme negative angle of attack (-20°), the force on the individual stabilizer was -11.2 N and was equal to the force generated on the fuselage. In turn, for the extreme positive angle, the force on the fuselage was 3.9 N so lower than the force on individual parts of the stabilizer. The entire stabilizer generates the lift force even 4 times greater than the force on the fuselage. The extreme values on the stabilizer occurred for the angles of -20° and 20° and were respectively equal to -22.4 N and 23.1 N. The lowest value of the total lift force for the tested aircraft was equal to -33.9 N, which corresponded to $\alpha = -20^\circ$, and its highest the value was 30.8 N for an angle of 20°.

![Figure 2. Drag force (left) and lift force (right) on the selected elements of the aircraft vs. the angle of attack.](image)

The last of the analysed parameters is the pitching moment in relation to the angle of attack (Figure 3). The trend of its total value is important for the stability of the research object. As the angle of attack increases, its value decreases approximately linearly. This proves that the stabilizer works correctly and ensures stability for the aircraft regardless of the angle of attack. Deviations from linearity and at the same time extreme moment values for the entire aircraft occur for the extreme angles of attack of -20° and 20° (9.9 Nm and -12.6 Nm, respectively). The angle for which the total moment was zero was -1.4°. The fuselage moment had a slightly negative value, which approached zero as the angle of attack increased. The smallest moment for this element equalled -2.4 Nm. As in the case of the drag force and the lift force, the pitching moments for the left and right stabilizer was identical so this parameter was analysed for the entire stabilizer. The stabilizer moment has a similar trend to that for the entire aircraft, with the difference that the stabilizer moment for each analysed angle has a slightly higher value (the
exception is $\alpha = 20^\circ$). Figure 4 shows the pressure distribution on the symmetry plane of the aircraft. For a large angle of attack ($\alpha = 20^\circ$), there was a high positive pressure of up to 250 Pa on the upper surface of the fuselage and tail booms, the leading edges of the lower part of the stabilizer and the mast.

![Figure 3. Pitching moment for the selected sections of the aircraft vs. the angle of attack.](image)

![Figure 4. Pressure distribution on the surface of aircraft and the symmetry plane.](image)

The positive pressure on the fuselage and tail booms translates to an increase in pressure on the plane of symmetry around these elements. It is visible in the form of areas with gradually increasing pressure on the plane of symmetry. The negative pressure occurred on the lower front part of the fuselage, the
rounded (streamlined) parts of the fuselage and the mast, and the leading edges of the upper part of the stabilizer. The extreme value of negative pressure was -823 Pa.

In the case of zero angle of attack, positive pressure occurred on the front upper part of the fuselage, the tail booms and all leading edges of the stabilizers. A large negative pressure of up to -590 Pa (extreme value for the entire aircraft) occurred on the streamlined part of the mast. The area of gradually increasing pressure on the symmetry plane at the nose of the aircraft and the tail booms was smaller compared to the case with a large negative angle of attack.

A large positive angle of attack results in a significant change in the pressure distribution compared to the two previous cases. Positive pressure occurred on the nose of the fuselage, mast, tail booms and the leading edges of the upper stabilizer. At the leading edges of the lower part of the stabilizer, a negative pressure of about -300 Pa was observed. Other larger areas of negative pressure up to about -400 Pa occurred on the streamlined parts of the fuselage and mast and the upper surface of the stabilizers. The area of gradually increasing pressure on the plane of symmetry near the nose of the aircraft changed its shape as it moved towards the bottom of the aircraft. The area near the tail booms was similar.

The distribution of drag, lift and pitching moment on individual parts of the stabilizer for the selected angles of attack were also analysed (Figure 5). Due to the existing symmetry of the geometry, the values on the right side of the stabilizer were analysed only.

![Figure 5](image)

**Figure 5.** Comparison of drag ($P_x$), lift ($P_z$) and pitching moment ($M_y$) for the selected angles of attack on the selected sections of the right stabilizer.

For a zero angle of attack, the drag force is small (below 0.2 N). The upper part has the largest share in its generation. For a large negative angle of attack ($\alpha = -20^\circ$), the drag force on all parts increases significantly (up to 1.6 N). The percentage of strength on the horizontal part also increases (43%), but
the upper part has the force greater than the bottom one (19% and 37% of the total generated force, respectively). For an angle of attack equal to 20°, a maximum force of 1.8 N occurred on the horizontal part. The force on the lower and upper parts was comparable and accounted for 28% of the total force on the right stabilizer.

The lift for \( \alpha = -20° \) had a negative value of -4.4 N and was comparable for the upper and horizontal parts (approx. 40% share). The power on the lower part was nearly twice less. For the extreme positive angle of attack, the greatest force of 4.8 N occurred on the horizontal part. The strength on the upper part was slightly greater than on the lower part (31% and 27% respectively).

The percentages for the pitching moment for the extreme angles of attack were similar to those for lift, but the sign of the value was opposite. For \( \alpha = -20° \), the extreme moment was about 2.5 Nm, and for \( \alpha = 20° \), it was -2.7 Nm.

Both for the lift force and pitching moment for the zero angle of attack, due to the negative values on the right upper part, their total value is reduced, which results in overstated percentages of individual elements, and the lift force and pitching moment on all parts of the stabilizer oscillated around zero.

4. Conclusions

The paper presents the results of numerical tests of autogyro aerodynamics with a double tail stabilizer. The research was carried out using the computational fluid dynamics method and Ansys Fluent software.

Drag, lift, pitching moment, pressure distribution on the surface of the entire aircraft and the plane of symmetry as well as forces and moment on individual sections of the stabilizer were calculated. The values of forces and moments allowed for a preliminary quantitative assessment of the aerodynamic performance of the analysed aircraft geometry. A comparative analysis with other objects should refer to dimensionless values, i.e. aerodynamic coefficients.

The performed tests made it possible to conduct a preliminary aerodynamics analysis of the research object. It was observed that the drag force as a function of the angle of attack on the stabilizers has a similar trend to that of the whole aircraft, and the fuselage drag has a relatively flat characteristic. The lift force on the fuselage and one of the stabilizer parts had a similar trend and values for the considered angles of attack. The stabilizers played an important role in the total lift force. The pitching moment on the fuselage took small negative values close to zero. The moment for the entire aircraft was characterised by a linearly decreasing trend, which proves good stability of the research object.

The analysis of the pressure distribution on the surface of aircraft and on the symmetry plane shows that the greatest positive pressure occurred on the fuselage nose and mast. Negative pressure occurred in the area of the streamlined edges, i.e. at the point of flow acceleration (according to Bernoulli's law). Changing the angle of attack changes the distribution of the positive pressure area in the front section of the aircraft and at the tail boom.

Significant differences in the values and percentage of the drag, lift and pitching moment depending on the angle of attack were observed. The horizontal section of the stabilizer is most important for the drag force. The percentages for the pitching moment for the extreme angles of attack were similar to those for the lift force, but it had an opposite sign. Changing the angle of attack from positive to negative results in a different distribution of forces and moment on the lower and upper part of the stabilizer.

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References

[1] Gudmundsson S 2014 *The Aircraft Design Process*. Epub ahead of print DOI: 10.1016/B978-0-12-397308-5.00001-5

[2] Dehaeze F, Barakos GN, Garipova LI, Kusyumov AN and Mikhailov SA 2017 Coupled CFD/CSD simulation of the helicopter main rotor in high-speed forward flight. *Russ Aeronaut*;
[3] Saraf AK, Singh MP, Chouhan TS 2017 Aerodynamic analysis of NACA0012 airfoil using CFD. *Int J Mech Prod Eng* **5** 21–25

[4] Shen J, Su Y, Liang Q and Zhu X 2018 Calculation and identification of the aerodynamic parameters for small-scaled fixed-wing UAVs. *Sensors (Switzerland)* **18** 1–18

[5] Czyż Z, Siadkowska K, Sochaczewski R 2019 CFD Analysis of Charge Exchange in an Aircraft Opposed-Piston Diesel Engine *MATEC Web Conf* **252** 04002

[6] Siadkowska K 2020 Aerodynamic measurement of the rotor blade for aviation application. In: *IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2020 - Proceedings - in proof*, Pisa

[7] Siadkowska K, Raczynski R, Wendeker M 2019 Numerical analysis of the rotor in the co-simulation methodology. *IOP Conf Ser Mater Sci Eng Pap*; 710. Epub ahead of print DOI: 10.1088/1757-899X/710/1/012009

[8] Kovalovs A, Barkanov E, Ruchevskis S, et al. 2017 Optimisation Methodology of a Full-scale Active Twist Rotor Blade. *Procedia Eng* **178** 85–95

[9] Coutu D, Braïlovski V, Terriault P 2010 Optimized design of an active extradors structure for an experimental morphing laminar wing. *Aerosp Sci Technol* **14** 451–458

[10] Skiba K 2019 Designing and FEM simulation of the helicopter rotor and hub *IOP Conf Ser Mater Sci Eng Pap*; 710. Epub ahead of print DOI: 10.1088/1757-899X/710/1/012003

[11] Sobieszek A, Wojtas M 2016 Composite rotor blades tests essential before mounting on gyroplane. *J KONES Powertrain Transp*; 23. Epub ahead of print DOI: 10.5604/12314005.1217289.

[12] Niemi JE, Raghu Gowda BV 2011 Gyroplane Rotor Aerodynamics Revisited - Blade Flapping and RPM Variation in Zero-g Flight. In: *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition* Epub ahead of print DOI: 10.2514/6.2011-1191

[13] Grabowski Ł, Czyż Z, Kurszczynski K 2014 Numerical Analysis of Cooling Effects of a Cylinders in Aircraft SI Engine. *SAE Tech Pap*; 2014-01–28. Epub ahead of print DOI: 10.4271/2014-01-2883

[14] Miraliakbari A, Hahn M, Engels J 2012 Vibrations of a Gyrocopter – an Analysis Using Imus. *ISPRS - Int Arch Photogramm Remote Sens Spat Inf Sci* **XXXIX-B1** 497–502

[15] Czyż Z, Karpiński P 2020 Numerical analysis of the impact of sideslip angle on load of the gyrocopter stabilizers *Aviation* **23** 114–122

[16] Czyż Z, Wendeker M 2020 Measurements of aerodynamic interference of a hybrid aircraft with multirotor propulsion. *Sensors (Switzerland)* **20** 1–14

[17] Czyż Z, Siadkowska K 2020 Measurement of air flow velocity around the unmanned rotorcraft. In: *IEEE International Workshop on Metrology for Aerospace, MetroAeroSpace 2020 - Proceedings - in proof*, Pisa

[18] Houston S, Thomson D 2017 On the modelling of gyroplane flight dynamics. *Prog Aerosp Sci* **88** 43–58

[19] Saeed AS, Younes AB, Islam S, et al 2015 A review on the platform design, dynamic modeling and control of hybrid UAVs. *2015 Int Conf Unnamed Aircr Syst ICUAS 2015* 806–815

[20] Pankonien AM 2015 *Smart Material Wing Morphing for Unmanned Aerial Vehicles*. University of Michigan, https://deepblue.lib.umich.edu/handle/2027.42/111533

[21] Czyż Z, Lusiak T, Karpiński P, Czarnigowski J 2018 Numerical investigation of the gyroplane longitudinal static stability for the selected stabilizer angles. *J Phys Conf Ser*; 1101. Epub ahead of print DOI: 10.1088/1742-6596/1101/1/012003