Numerical investigation of the gyroplane longitudinal static stability for the selected stabilizer angles

Z Czyż¹, T Łusia³, P Karpiński¹ and J Czarnigowski¹
¹ Lublin University of Technology, Faculty of Mechanical Engineering, Department of Thermodynamics, Fluid Mechanics and Aviation Propulsion Systems, Nadbystrzycka 36 Str., 20-618 Lublin, Poland
² Polish Air Force Academy, Department of Airframe and Engine, 35 Dywizjonu 303 Str., 08-521 Dęblin, Poland
z.czyz@pollub.pl

Abstract. Stability is a key aspect for aircraft as it directly affects its flight balance and manoeuvre capabilities. This numerical research with Ansys Fluent investigates an airflow around a model of the designed gyrocopter – Aduster to examine its static longitudinal stability for the given ranges of horizontal stabilizer angles and angles of attack. Our calculations give certain aerodynamic forces and moments. The paper investigates drag, lift, a pitching moment at the given angles as well as gives the calculated coefficients of those forces and the pitching moment. The research results and the stability criterion enable us to analyse our gyrocopter’s static longitudinal stability.

1. Introduction

Gyrocopters have recently been gaining importance in the general aviation, especially in the air cargo sector and sport. Compared to light fixed-wing aircraft, they are distinguished by their short take-off and landing; and compared to light helicopters, their purchasing and operating costs are lower and operation is simpler. Currently, numerical calculations are very advanced and enable a precise modeling of gyrocopter flight mechanics. However, flight phenomena can be precisely described if certain additional data is applied. To validate a model, data about physical phenomena and processes that determine a behavior of aircraft, including geometry, mass, inertia and at least aerodynamic characteristics of rotors and airfoils are indispensable. The work in [1] presents the aspects of a mathematical modeling of gyrocopter flight dynamics including trim, stability and control with a flight test data validation. The same author in his previous work [2] applied an advanced mathematical model of a gyrocopter and aerodynamic forces and moments to investigate gyrocopter longitudinal stability. According to this research, a rotorspeed degree of freedom is an indispensable parameter in this type of modeling. The work [3] discusses the research into gyrocopter stability and flight control based on flight test data. The paper [4] presents a mathematical model of a vehicular towed autogyro system. To control the pitch angle so maintaining longitudinal stability, a PID controller is applied. The pitch angle was controlled with an inner altitude control loop. Another study using a mathematical model of gyrocopter flight dynamics is in [5] where a non-linear mathematical model of a small unmanned gyrocopter was created to investigate how a location of the center of gravity affects stability. This research was initiated in the research in [6] which had studied the drag acting on the gyrocopter components. A similar type of research into the drag and lift acting on the gyrocopter is discussed in [7]. Here, the research focuses...
on the static longitudinal stability of the research aircraft to investigate the impact of the angle of the horizontal stabilizer on stability and the generated total lift within a given range of angles of attack.

CFD (Computational Fluid Dynamics) calculations are a widely-used method to research aircraft. They are cheap, fast and easy to examine even large aircraft structures. Parameters like aerodynamic forces and moments for given airflow conditions are calculated here. The work in [8] applied this method to optimize a rotor design in a light gyrocopter. The author developed a set of dedicated gyrocopter airfoils as a competitive alternative to classical aerodynamic airfoils used in designing gyrocopter blades. The same applies to main rotor blades created with newly designed airfoils.

A CFD method was also applied to evaluate how a main rotor, its configuration and flight conditions influence gyrocopter aerodynamic characteristics and stability [9]. It was found that the airflow generated by a main rotor changes the most important aerodynamic coefficients and stability derivatives of the gyroplane body. The work in [10] presents the methodology of designing and optimizing gyroplane rotors with a CFD method. The authors in [11] used a CFD technique to create a dynamic model of the designed unmanned gyrocopter. The researchers in [12] made calculations of a cooling system in the designed gyrocopter drive. However the results of CFD engine cooling system presented in [13] show that the cooling capabilities are strongly dependent on surrounding geometries.

Numerical research can be validated with wind tunnel experiments, e.g. the wind tunnel research in [14] enabled the aerodynamic characteristics of the researched model of a gyrocopter. The pitching moment coefficient versus an angle of attack for different gyrocopter configurations, i.e. with or without stabilizers. The research shows that the fuselage reduces nearly by half the degree of the pitching moment generated by the tail beam. The fuselage without tail beams was unstable within the entire range of angles of attack. Wind tunnel research can be extended by a PIV visualization of an airflow around a research object. A PIV method was discussed in [15] to specify aerodynamic characteristics of a quad-rotor autogyro model. Moreover, the research in [16] uses a PIV method to describe the velocity field of the airflow around this quad-rotor autogyro model. The calculations enabled them to determine the component velocities as a function of a vertical coordinate. Accordingly, a comparative analysis of the research aircraft configuration was possible. Wind tunnel research for larger objects is much more expensive so alternative methods to generate an airflow around a research object, e.g. using a motor vehicle emerge. Such an approach is discussed in the work [17] where the drag of a gyrocopter model was examined on a platform mounted on a car roof. A moving vehicle caused an external airflow around the model. A difference between this experiment and a computer simulation consisted chiefly in airflow disturbances around the vehicle. The authors suggested an additional plate to be placed to separate the airflow around the research area and the vehicle. Such a plate can keep a research object in a non-disturbed flow as it is isolated from a vehicle.

2. **Gyrocopter model and research plan**

A solid model of the research gyrocopter was created in CATIA V5. The aircraft was segmented as shown in Figure 1. This segmentation enabled us to identify aerodynamic forces and moments acting on its individual parts. Figure 2 shows the dimensions of the research gyrocopter and its position relative to the global coordinate system (center of gravity). It is a Cartesian right-handed longitudinal system with an x-axis along the axis of symmetry of the gyrocopter, the transverse y-axis and the vertical z-axis. The aerodynamic moment generated relative to the y-axis is a pitching moment. Angle \( \alpha \) is clockwise positively calculated. Sideslip angle \( \beta \) for this test series was 0°. Horizontal stabilizer angle \( \gamma \) varied in our calculations.
A solid model of the research gyrocopter was prepared for CFD calculations by being imported into Ansys Fluent in a Design Modeler module and removing all types of discontinuities, holes, sharp and fragmented edges and surfaces. Such a solid gyrocopter model was centrally placed in a rectangular processing domain of 36416 x 33148 x 32798 mm (length x height x width) that was created with a function of Enclosure (Figure 1). On the walls of the domain, an velocity inlet and an pressure outlet were defined. The components of the gyrocopter were set as wall. The type of calculations was pressure-based in steady conditions. The airflow was as ideal gas. A turbulence model was k-ω SST which uses two equations, i.e. one of them describes turbulence kinetic energy k and the other one describes a specific dissipation of kinetic energy ω. This model is also capable of restricting shear stress transport (SST).

Turbulence intensity was assumed as 1%, a turbulence viscosity coefficient as 5, air temperature as 288 K (15 °C), dynamic viscosity as 1.7894·10⁻⁵ kg/ms, and air velocity as 28 m/s (approx. 100 km/h). A mesh of the model was created of tetrahedrons with an advanced function of Curvature (Figure 3). On the surface of the entire gyrocopter, a wall layer was created by means of Inflation and Smooth Transition. There was defined 7 layers of a 1.15 growth rate. The mesh effect was investigated. The domain was calculated with different number of elements. The number of elements and elements size which does not affect the results of calculations has been found. The mesh consisted of approx. 6.7 million elements.
For this model of the gyrocopter, 55 measuring points were defined by an angle of attack $\alpha$ and horizontal stabilizer angle $\gamma$. The angle of attack ranged from $-25^\circ$ to $+25^\circ$, every $5^\circ$ and the horizontal stabilizer angle ranged from $-10^\circ$ to $+10^\circ$, every $5^\circ$. For each measuring point, the drag, lift and pitching moment that acted on the gyrocopter components were recorded to calculate corresponding aerodynamic coefficients from formulas (1) and (2):

$$C_{x,z} = \frac{P_{x,z}}{0.5 \rho v^2 \pi R^2}$$  \hspace{1cm} (1)

$$C_{my} = \frac{M_y}{0.5 \rho v^2 \pi R^3}$$  \hspace{1cm} (2)

where: $\rho = 1.226$ kg/m$^3$ – air density, $v = 28$ m/s – airflow velocity, $R = 5$ m – rotor radius.

The stability criterion is the case when the total pitching moment acting on the aircraft is negative when disturbance occurs (3):

$$\frac{\delta M_y}{\delta \alpha} < 0$$  \hspace{1cm} (3)

Static longitudinal stability was examined according to this stability criterion.

3. Results and discussion
The numerical calculations gave the values of drag, lift and pitching moment as a function of angle of attack at different horizontal stabilizer angles applied to individual gyrocopter components. Then, the total values of the aerodynamic forces, pitching moment and the corresponding aerodynamic coefficients were calculated. Additionally, the pressure contours and velocity contours in the plane of symmetry of the research gyrocopter for the given angles and settings of the horizontal stabilizer were plotted.

Figure 4 shows the total drag acting on the research gyroplane (a) and the drag coefficient (b). If a horizontal stabilizer is added, the drag at high angles of attack significantly increases. Its lowest value, i.e. approx. 200 N, regardless of a horizontal stabilizer angle, occurs near an angle of attack equal to 0. Increased and decreased angles of attack result in higher drag. The highest drag, i.e. more than 800 N is generated at extremal angles of attack, i.e. $-25^\circ$ and $+25^\circ$. 
Figure 4. Total drag (a) and drag coefficient (b) versus the angle of attack at the given horizontal stabilizer angles.

Figure 5 shows the total lift acting on the research gyrocopter and the lift coefficient. If there is no horizontal stabilizer, lift increases approximately linearly as the angle of attack increases. If a horizontal stabilizer mounted, there are three areas where the lift increases as the angle of attack increases. The nature of this growth changes according to the value of the angles of attack and horizontal stabilizer angles. For each of the horizontal stabilizer angles, an area of a linear correlation between the lift and an angle of attack can be distinguished. As horizontal stabilizer angles increase, this area shifts towards lower angles of attack. The angle of lift equals zero behaves in a similar way. The largest positive lift, i.e. approx. 1200 N occurs at the largest angle of attack, whereas the highest negative lift, i.e. approx. -1000 N occurs at the smallest angle of attack.

Figure 6 shows the pitching moment acting on the research gyrocopter and the pitching moment coefficient. The research in [1] shows that at high absolute angles of attack the horizontal stabilizer has the largest share in generating the pitching moment. If there is no horizontal stabilizer, the pitching moment increases roughly linearly as the angle of attack increases and is 0 at an angle of attack of approx. 4°. The stabilizer reverses this correlation and three areas with a decreasing pitching moment as an angle of attack increases occur. The nature of this decrease changes according to the angle of attack and the horizontal stabilizer angle. For each of the horizontal stabilizer angles, just as it is for lift, an area of the linear correlation between the pitching moment and an angle of attack can be distinguished. As the horizontal stabilizer angle increases, this area shifts towards smaller angles of attack. The angle corresponding to the maximum pitching moment (positive) shifts towards smaller angles as the
horizontal stabilizer angle decreases. The minimal pitching moment (negative) occurs at the largest angle of attack regardless of the horizontal stabilizer angle. The contour of the pitching moment is similar to the stabilizer angle ranging between -5° and -10° at the angle of attack less than -10° because at an horizontal stabilizer angle of -10° and the given range of the angle of attack, there is probably the phenomenon of air stream detachment, which decreases lift acting on the stabilizer and reduces the pitching moment so stability is lost.

Figure 6. Pitching moment (a) and the pitching moment coefficient (b) versus the angle of attack for the given horizontal stabilizer angles.

The method of least squares enabled the approximating functions of the pitching moment as a function of the angle of attack for each horizontal stabilizer angle. Later, the derivatives of these functions after the angle of attack were calculated and their values at points corresponding to the defined measuring points were calculated. The approximating functions of the pitching moment according to the angle of attack for the given horizontal stabilizer angles γ are given in equations (4)-(8):

\[ \gamma = -10^\circ: \quad C_{my}(\alpha) = -9.239215686627466 \cdot 10^{-11} \cdot \alpha^6 + 1.38461538461564 \cdot 10^{-10} \cdot \alpha^5 + 
+ 1.06396681749624 \cdot 10^{-7} \cdot \alpha^4 - 4.20163170163386 \cdot 10^{-8} \cdot \alpha^3 - 
- 4.117737556514 \cdot 10^{-5} \cdot \alpha^2 - 0.000276308857808854 \cdot \alpha + 0.00677889757301523 \]

\[ \gamma = -5^\circ: \quad C_{my}(\alpha) = -6.31111111111114 \cdot 10^{-11} \cdot \alpha^6 - 2.30769230769235 \cdot 10^{-10} \cdot \alpha^5 + 
+ 6.8709401794019 \cdot 10^{-8} \cdot \alpha^4 + 5.0856643566437 \cdot 10^{-7} \cdot \alpha^3 - 
- 0.0000253538150738151 \cdot \alpha^2 - 0.0004921534965035 \cdot \alpha^1 + 0.003481818181818 \]

\[ \gamma = 0^\circ: \quad C_{my}(\alpha) = -1.7777777777745 \cdot 10^{-12} \cdot \alpha^6 - 4.2051282012804 \cdot 10^{-10} \cdot \alpha^5 - 
- 5.82905982906027 \cdot 10^{-9} \cdot \alpha^4 + 8.88461538461527 \cdot 10^{-7} \cdot \alpha^3 + 
+ 8.5173271732826 \cdot \alpha^2 - 0.0005991515151513 \cdot \alpha^1 - 0.000524475424475529 \]

\[ \gamma = 5^\circ: \quad C_{my}(\alpha) = 1.8248366030736 \cdot 10^{-11} \cdot \alpha^6 - 1.58974358974371 \cdot 10^{-10} \cdot \alpha^5 - 
- 3.5626445499766 \cdot 10^{-8} \cdot \alpha^4 + 4.52972027972038 \cdot 10^{-7} \cdot \alpha^3 + 
+ 0.00018664031719918 \cdot \alpha^2 - 0.00048728927738929 \cdot \alpha^1 - 0.004356354092966 \]

\[ \gamma = 10^\circ: \quad C_{my}(\alpha) = 3.05359477124189 \cdot 10^{-11} \cdot \alpha^6 + 3.89743589743589 \cdot 10^{-10} \cdot \alpha^5 - 
- 5.0013071854254 \cdot 10^{-8} \cdot \alpha^4 - 2.24475524475524 \cdot 10^{-7} \cdot \alpha^3 + 
+ 0.00026526733397323 \cdot \alpha^2 - 0.0002762409324093 \cdot \alpha^1 - 0.00730843274372687 \]

Figure 7-8 depict the examples of the pressure contours and velocity contours on the plane of symmetry of the research gyrocopter at the extremal angle of attack and horizontal stabilizer angle.
Figure 7. Pressure contour (a) and velocity contour (b) on the plane of symmetry of the gyrocopter at $\alpha = +25^\circ$, $\gamma = -10^\circ$.

Figure 8. Contour of pressure (a) and contour of velocity (b) on the plane of symmetry of the gyrocopter at $\alpha = +25^\circ$, $\gamma = +10^\circ$.

Figure 9 shows derivatives $\delta M_y/\delta \alpha$ according to angles of attack $\alpha$ and horizontal stabilizer angles $\gamma$. The positive derivative was marked with a red color.

Figure 9. Derivatives $\delta M_y/\delta \alpha$ versus angles of attack $\alpha$ and horizontal stabilizer angles $\gamma$: (a) and (b).

4. Conclusions

This paper discusses the static longitudinal stability of the gyrocopter at different horizontal stabilizer angles and angles of attack. The drag, lift and pitching moment at the given stabilizer angles and angles of attack were achieved from the numerical calculations of the created model with Ansys Fluent. The investigation focused on how the aerodynamic characteristics of the research gyrocopter are impacted by the horizontal stabilizer angles. The aircraft stability criterion based on the derivative of the pitching moment enabled us to examine the stability of the research gyrocopter. The calculations enabled us to identify angles of attack at which the research object lost its stability. For all of the examined horizontal
stabilizer angles, derivative $\delta M/\delta \alpha$ was positive, i.e. stability was lost at angle $\alpha = -25^\circ$. In addition, at $\gamma = 0^\circ$, this derivative remained positive at the next angle of attack $\alpha = -20^\circ$. There were four more positive values out of the angles, i.e. at $\alpha = -10^\circ$ and $-5^\circ$ if $\gamma = -10^\circ$, at $\alpha = 10^\circ$ and $25^\circ$ if $\gamma = 10^\circ$ (see Figure 12). This is mainly due to the loss of lift force on the stabilizer. For the angle of attack $\alpha = -10^\circ$, $\alpha = -5^\circ$ and $\gamma = -10^\circ$ the real angle of attack of the stabilizer relative to airflow equals respectively $-15^\circ$ and $-20^\circ$. Then the lift force on the stabilizer is reduced. An analogous situation occurs for the $\gamma = 10^\circ$. It should be noted that stability is lost not only at the given points but within a range of angles. Figure 12 (right) depicts derivatives $\delta M/\delta \alpha$ versus the angle of attack and this correlation enables us to estimate stability ranges and values at which the object remains neutrally stable. It is important to have as much stability margin as possible; however, too high stability is adverse to aircraft maneuverability.

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**References**

[1] Houston S and Thomson D 2017 On the modelling of gyroplane flight dynamics. *Progress in Aerospace Sciences* vol 88 pp 43-58

[2] Houston S S 1996 Longitudinal stability of gyroplanes *The Aeronautical Journal* vol 100 no 991 pp 1-6

[3] Houston S S 1998 Identification of autogyro longitudinal stability and control characteristics *Journal of Guidance, Control, and Dynamics* vol 21 no 3 pp 391-399

[4] Ma Y Cai Z Liu N and Wang Y 2016 System composition and longitudinal motion control simulation of vehicular towed autogyro *Guidance, Navigation and Control Conference* pp 1018-1023

[5] Xiang C Wang X Ma Y and Wang Y 2014 Modeling and modal responses analysis of an unmanned small-scaled gyroplane *Guidance, Navigation and Control Conference* pp 262-268

[6] Czyż Z Karpiński P Łusiak T and Szczepeanik T 2017 Numerical analysis of the influence of particular autogyro parts on the aerodynamic forces *ITM Web of Conferences* vol 15 p 07008

[7] Czyż Z Ilhan I Akcay M and Czarnigowski J 2017 Air flow analysis around the autogyro fuselage *Journal of Technology and Exploitation in Mechanical Engineering* vol 3 no 1 pp 13-20

[8] Stalewski W 2017 Improvement and optimisation of gyroplane performance *Prace Instytutu Lotnictwa*

[9] Figat M 2017 Aerodynamics analysis of the main rotor influence on the static stability of the gyroplane *Aircraft Engineering and Aerospace Technology* vol 89 no 5 pp 663-670

[10] Stalewski W 2016 Aerodynamic design of modern gyroplane main rotors *Prace Instytutu Lotnictwa*. 

[11] Lin Q Cai Z and Wang Y 2014 Design, model and attitude control of a model-scaled gyroplane *Guidance, Navigation and Control Conference* pp. 1282-1287

[12] Grabowski L Czyż Z and Kruszczyński K 2014 Numerical Analysis of Cooling Effects of a Cylinders in Aircraft SI Engine *SAE Technical Paper* 2014-01-2883

[13] Pietykowski K Tulwin T 2015 Aircraft Radial Engine CFD Cooling Model *SAE INTERNATIONAL JOURNAL OF ENGINES* vol 8 no 1 pp 82-88

[14] Coton F N and Smrcek L 1998 Aerodynamic characteristics of a gyroplane configuration *Journal of Aircraft* vol 35 no 2 pp 274-279

[15] Krzyśiak A 2017 Wind tunnel tests of quad-rotor autogyro model *Journal of KONES* vol 24 no 1 pp 231-238

[16] Czyż Z and Stryczniewicz W 2018 Investigation of Aerodynamic Interference in a Multirotor by PIV Method *Advances in Science and Technology. Research Journal* vol 12 no 1 pp 106-114

[17] Czyż Z Magryta P and Szlachetka M 2015 Experimental investigation of the impact of flight speed on drag force in the autogyro model. *Advances in Science and Technology. Research Journal* vol 9 no 26 pp 89-95