CFD investigation of the main rotor for an unmanned helicopter

C Królak¹, Z Czyż¹, K Siadkowska² and R Kliza²

¹ Military University of Aviation, Aeronautics Faculty, 35 Dywizjonu 303 St., 08-521 Dębлин, Poland
² Lublin University of Technology, Faculty of Mechanical Engineering, 36 Nadbystrzycka St., 20-618 Lublin, Poland

z.czyz@law.mil.pl

Abstract. The paper presents the CFD analysis of the main rotor of the unmanned helicopter model with a maximum take-off mass of up to 150 kg. The calculations were performed in ANSYS Fluent software. The results of the work are the relationship between the lift force generated by the main rotor as a function of the blade angle of attack. The results are presented for the three considered rotational speeds i.e. 1400, 1600, 1800 rpm. As the angles of the blades of attack increases, an increase in the rotor lift force, torque, and power requirement of the tested main rotor was observed. Additionally, the power required to drive a carrier rotor for the three speeds in question was calculated. Examined changes in the power requirement of the main rotor also showed a percentage increase when changing the α and increasing the rotational speed. The result based on the numerical calculations for three blades main rotor model were presented in tables and diagrams.

1. Introduction
In the 21st century, the conducting of research on aircraft and their components are inseparably connected with numerical fluid dynamics [1-3]. This method is widely used in many fields, e.g. mechanical, marine and biomedical engineering, for calculations of the aerodynamics of aircraft and vehicles and rotating machines [4-6]. The high level of advancement of numerical tools results in the necessity to have extensive knowledge to properly simulate material or operational parameters. Although the principle of software operation is based on known physical equations, numerical algorithms, and material properties, the researcher’s skills and knowledge still play a major role.

The commercial CFD software consists of three basic modules. These are pre-processing, calculation solver and post-processing. The first one includes the definition of geometry and computational domain, element grid generating, selection of phenomena to be modelled, definition of fluid properties, and boundary conditions. In the next stage, there is an integration of fluid mechanics equations, discretisation, and iterative solving of algebraic equations. Post-processing includes grid display, vector and surface diagrams, animations, and elements related to the visualisation of simulation results.

The determination of force and aerodynamic coefficients as early as in the 20th century was associated primarily with tunnel tests of scaled models [7]. Naturally, the research on physical, real objects better represents the occurring phenomena, however, their cost induced engineers to develop simulation methods. Nowadays, it is common practice to initially incorporate modelling with the
computer techniques [8], and then to carry out studies on scaled objects [12-14] in order to finally carry out studies on the real object, most often on a measured test stand [15-19] or in a wind tunnel [20].

This paper focuses on the CFD research of the blades of the main rotor. The tested main rotor together with the blades is a research object intended for the analysis of active control of the blade twist angle[21]. Its important feature is the ability to supply power to the actuators located in the blades [23-24] in order to control their twist angle without using external moving elements in the blades [25]. Numerous studies concerning the possibility of controlling the rotor blade shape using various subsystems are carried out. These include Gurney flap [26-27], piezoelectric fibres [28] and shape memory material [29]. The designed rotor elements require aerodynamic tests, which is the subject of this work.

2. Research object and methodology
The test object is a rotor blade dedicated to the unmanned helicopter with a maximum take-off weight of up to 150 kg (Figure 1). The rotor diameter is 2 m. The rotor blades are based on three different aerodynamic profiles: NACA 23018, NACA 23012, and NACA 23009.

![Figure 1. Research object: view of the complete model (left) and simplified geometric model (right).](image)

A simplified geometrical model of the rotor was first surrounded by a cylinder (disk) and then, using the Enclosure function, an environment was created, creating a computing domain with dimensions of $4100 \times 14100 \times 6200$ mm. The radius of the disc directly surrounding the blade is 2100 mm and the height is 200 mm. The domain created in this way is shown in Figure 2.

![Figure 2. View of calculation domain.](image)
Figure 3 shows the view of a single main rotor blade after discretisation. The grid density is visible along the attack and run-off edges. The total number of grid elements was about 6 million. The calculations were made for four different blade angles of attack (0°, 5°, 10°, and 15°) and three different rotational speeds: 1400, 1600, and 1800 rpm which correspond to angular velocity values: 146.53, 167.47, and 188.40 rad/s.

The numerical calculations were done with computational solver Ansys/Fluent. Turbulence model $k$-$\omega$ was used. The calculation was performed as a transient with the mesh motion option. The temperature of the working fluid was set to 288 K. Additionally, the turbulent intensity was set to 0.5%, and the turbulent intensity ratio of 5%. Table 1 shows the values of the calculated time step necessary to perform the calculations. One time step corresponds to a 10° main rotor rotation. The analysis was set to 108 steps which correspond to three full rotor rotations.

![Figure 3. View of the main rotor blade after discretisation.](image)

| Rotational speed (1/min) | Angular velocity (rad/s) | Frequency of rotation (1/s) | Time of one rotation (s) | Time step (s) |
|-------------------------|--------------------------|----------------------------|-------------------------|---------------|
| 1400                    | 146.53                   | 23.33                      | 0.04286                 | 0.00119       |
| 1600                    | 167.47                   | 26.67                      | 0.03750                 | 0.00104       |
| 1800                    | 188.40                   | 30.00                      | 0.03333                 | 0.00093       |

3. Results

Figure 4 shows the relationship between the lifting force generated by the main rotor as a function of the blade angle of attack. The results are presented for the three considered rotational speeds i.e. 1400, 1600, 1800 rpm. As the angles of the blades of attack increase, an increase in the rotor lift force, torque, and power requirement of the tested lifting rotor was observed. The increase in speed from 1400 rpm to 1600 rpm resulted in an increase in thrust of 18.93% for the angle of attack $\alpha = 5^\circ$.

For angles $\alpha = 10^\circ$ and $\alpha = 15^\circ$ this increase was 26.21% and 43.63%, respectively. The increase in speed from 1400 rpm to 1800 rpm resulted in a 55.83% increase in thrust for angles $\alpha = 5^\circ$. For angles $\alpha = 10^\circ$ and $\alpha = 15^\circ$ this increase was 58.34% and 56.01%, respectively. For the angle of attack $\alpha = 0^\circ$, the thrust force changed its turn to the opposite acting “down” and took the value equal to -12.68 N. The increase was 44.81% for a speed change from 1400 rpm to 1600 rpm and 99.17% for a speed change from 1400 rpm to 1800 rpm. Figure 4 also shows the relationship between the torque generated by the supporting rotor as a function of the blade angle. The observed increase in torque by increasing the speed from 1400 rpm to 1600 rpm was 32.49% for an angle of attack $\alpha = 5^\circ$. For angles $\alpha = 10^\circ$ and $\alpha = 15^\circ$ the increase was 33.93% and 42.04%, respectively. The increase in speed from 1400 rpm to 1800 rpm resulted in a 60.64% increase in torque for an angle of attack $\alpha = 5^\circ$. For angles $\alpha = 10^\circ$ and $\alpha = 15^\circ$, this increase was 59.60% and 58.42%, respectively. For angles $\alpha = 0^\circ$, the increase was 27.24% for a...
change of speed from 1400 rpm to 1600 rpm and 57.61% for a change of speed from 1400 rpm to 1800 rpm.

**Figure 4.** Lift force (left) and torque (right) as a function of the blade angle of attack.

Figure 5 shows the power required to drive a carrier rotor for the three speeds in question. Examined changes in the power requirement of the main rotor also showed a percentage increase when changing the $\alpha$ and increasing the rotational speed. An increase in speed from 1400 rpm to 1600 rpm increased the power requirement by 51.42% for an angle of attack $\alpha = 5^\circ$. For angles $\alpha = 10^\circ$ and $\alpha = 15^\circ$ the increase was 53.06% and 62.34%, respectively. When changing the speed from 1400 rpm to 1800 rpm, the power requirement increased by 106.54% for the angle of attack $\alpha = 5^\circ$. For angles $\alpha = 10^\circ$ and $\alpha = 15^\circ$ this increase was 105.21% and 103.68% respectively. For angles $\alpha = 0^\circ$, the increase was 45.41% for a speed change from 1400 rpm to 1600 rpm and 102.64% for a speed change from 1400 rpm to 1800 rpm.

**Figure 5.** The power requirement for the drive of the main rotor for different rotational speeds.
Besides, the pressure generated on the blades at an angle of $\alpha = 15$ was checked for all three speeds $n = 1400, 1600, 1800$ rpm. The article presents an exemplary visualisation of pressure distribution for the rotational speed $n = 1800$ rpm. The pressure range was from -602.4 hPa to 208.9 hPa. This is the pressure measured concerning the standard atmosphere. Therefore, in such a case the resulting positive or negative pressure should be added to 1013.25 hPa. The following figures (Figure 6) measure the resulting pressure and specify its distribution on individual parts of the carrier rotor blade.

![Pressure Contour on top and bottom blade surface.](image)

**Figure 6.** Pressure contour on top and bottom blade surface.

4. Conclusions
The main aim of this work was to calculate the flow of the carrier rotor blades in order to obtain aerodynamic characteristics. In addition to the pressure contours shown for $n=1800$ rpm, the pressure values for the other speeds were also measured. For rotational speed $n = 1600$ rpm the pressure range was from -461.6 hPa to 171.7 hPa and for rotational speed $n = 1400$ rpm the pressure range was from -298.2 hPa to 124 hPa. Since the analysed rotor reached the maximum thrust of 919 N for the angle of attack $\alpha = 15^\circ$ at 1800 rpm, it is recommended to optimise the geometric model of the rotor blades. The value generated by the rotor represents 62.5% of the required thrust. The purpose of the proposed optimisation is to achieve a thrust force of 1471.5 N which corresponds to a maximum starting mass of 150 kg. Modification of geometrical blade features will be the subject of further articles related to the CFD analysis of load-bearing rotors and wind tunnel tests.

**Acknowledgments**
This work has been financed by the National Centre for Research and Development under the LIDER program. Grant Agreement No. LIDER/45/0177/L-9/17/NCBR/2018.

**References**

[1] Comis Da Ronco C, Ponza R and Benini E 2015 *Comput Methods Appl Mech Eng* 285 255–290
[2] Czyż Z, Siadkowska K and Sochaczewski R 2019 *MATEC Web Conf* 252 04002
[3] Czyż Z, Łusiak T, Karpiński P and Czarnigowski J 2018 *J. Phys. Conf. Ser.* 1101(1) 012003
[4] Bai C and Wang W 2016 *Renew. Sustain. Energy Rev.* 63 506-519
[5] Batrakov A, Kusyumov A, Mikhailov S and Barakos G 2018 *Aerosp. Sci. Technol.* 77 704-712
[6] Pietrykowski K, Karpiński P and Mączka R 2020 *International Review on Modelling and Simulations* 13(1) 1-7
[7] Berry J D 1987 *NASA Technical Memorandum* 89053 87-B-7
[8] Perera G, Jagathsinghe H, Dilshan S, Sudaraka M and Rangajeeva S 2016 *Proceedings in Engineering, Built Environment and Spatial Sciences, 9th International Research Conference-"
KDU (Sri Lanka) 144-150

[9] Han D, Pastrikakis V and Barakos G 2016 *Aerosp. Sci. Technol.* **54** 164-173

[10] Saraf A, Singh M and Chouhan T 2017 *Int. J. Mech. Prod. Eng.* **5** 21-25

[11] Czyż Z and Siadkowska K 2020 *IEEE 7th International Workshop on Metrology for AeroSpace - MetroAeroSpace* (Pisa, Italy) pp 625-629

[12] Czyż Z and Wendeker M 2020 *Sensors* **20**(12) 3360

[13] Czyż Z and Karpiński P 2020 *Aviation* **23**(4) 114-122

[14] Czyż Z, Karpiński P and Stryczniewicz W 2020 *Sensors* **20**(19) 5537

[15] Sobieszek A and Wojtas M 2016 *J. KONES Powertrain Transp.* **23**(4) 487-494

[16] Sartori D and Yu W 2019 *J. Intell. Robot. Syst. Theory Appl.* **96** 529-540

[17] Grabowski Ł, Czyż Z and Porzak M 2018 *Transport* **33** 773-778

[18] Naik C and Vijaya Kumar R 2018 *Mater. Today Proc.* **5** 4653-4668

[19] Stepanov R and Mikhailov S 2017 *MATEC Web Conf.* **115** 02013

[20] Siadkowska K 2020 *Adv. Sci. Technol. Res. J.* **14** 4

[21] Siadkowska K 2020 *IEEE 7th International Workshop on Metrology for AeroSpace - MetroAeroSpace* (Pisa, Italy) pp 610-614

[22] Siadkowska K, Raczyński R and Wendeker M 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **710** 012009

[23] Fortini A, Suman A, Merlin M and Garagnani G 2015 *Mater. Des.* **85** 785-795

[24] Kovalovs A, Barkanov E, Ruchevskis S and Wesolowski M 2017 *Procedia Eng.* **178** 85-95

[25] Pastrikakis V, Steijl R, Barakos G and Malecki J 2015 *J. Fluids Struct.* **53** 96-111

[26] Pastrikakis V, Steijl R and Barakos G 2016 *Aeronaut. J.* **120** 1230-1261

[27] Sarkar P and Raczyński R 2017 *Recent Progress in Flow Control for Practical Flows*, ed Doerffer P, Barakos G and Luczak M (Springer International Publishing) pp 126-135

[28] Latalski J 2011 *Eksploatacja i Niezawodność - Maintenance and Reliability* **52** 72-78

[29] Epps J and Chopra I 2001 *Smart Mater. Struct.* **10** 104