Experimental study of the impact of the number of blades on the profile drag of UAV helicopter rotors in hover

F Panayotov¹,², I Dobrev³, F Massouh³ and M Todorov¹

¹Technical University of Sofia, Department of Air Transport, blvd. Kliment Ohridski 8, 1000 Sofia, Bulgaria
²Arts et Métiers – ParisTech, LIFSE, blvd. L’Hôpital 151, 75013 Paris, France
³E-mail: fpanayotov@tu-sofia.bg

Abstract. Due to the motion of tip and root vortices of helicopter rotor blades and the inevitable blade-vortex interactions in multi-blade rotors, the profile drag of all individual blades is increased, when compared to the absence of any blade-vortex interaction. Different factors like the speed of rotation of the rotor and the number of blades greatly impact the magnitude of the profile drag increase. This effect is additionally worsened with the low-Reynolds operational conditions of small-sized UAV helicopter rotors. In addition, there is an initial upward motion of the tip vortex and thus there are three scenarios for the blade-vortex encounter, depending on whether the vortex emitted by the previous blade is still above, on or below the plane of rotation of the blades. All those uncertainties motivated the authors to carry-out this present experimental study. The results are shown in a convenient form. In hover, the profile drag increase is shown to be greater with increased number of blades and higher rotational speeds as there is less time for the preceding vortex to clear the path of the following blade.

1. Introduction
Due to their simplistic design, low-cost control systems and the great variety of on-board electronics and sensors, the rotary-wing unmanned aerial vehicle (UAV) systems have taken their place in our society. Their use has rapidly increased in all spheres of human activities, finding applications in the commercial, agricultural, leisure, security and military sectors. The rotary-wing systems have a unique hovering ability, as well as the capability to perform vertical take-offs and landings. Those properties make them quite suitable for various purposes, like on-spot observation, etc.

The rotors of small-sized rotary-wing UAVs operate in low-Reynolds flow conditions, as they must provide adequately high aerodynamic efficiency of the rotor. While gradually reaching the technological limitations in battery and fuel-cell technologies, in light-weight structural materials and in the field of miniaturization of electronic components, it is a must to fully explore the rotor aerodynamics in low-Reynolds flow conditions. The key is to understand the impact of all various geometrical parameters on the overall aerodynamics efficiency of small-size rotors. For that purpose the studies on the impact of various geometrical parameters on the aerodynamic performance of small-scale UAV rotors have intensified significantly in recent years.

The absence of precise mathematical models for the description of the complex nature of low-Reynolds flows, as well as for adequate predictions of the thickness of the boundary layers or for phenomena like laminar separation bubbles and blade-vortex interactions, makes all efforts for an
analytical and computational evaluation of the aerodynamics performance of such rotors quite challenging. For those reasons the development of facilities and methodologies for experimental testing plays an important role in the further improvement of the aerodynamic efficiency of small-sized rotary wing propulsion systems.

Article [1] is a good example of an early pioneering work, in which the author estimates the variation of the lift and profile-drag for the tested airfoil for a wide range of Mach tip speeds and pitch angle settings of the blades. The study also reveals the hover performance of a large-scale helicopter rotor with blades of NACA0012 airfoil. It was found out that the studied airfoil generates larger lift and lower profile-drag than expected, when compared with the previously obtained experimental two-dimensional airfoil data.

In [2], the authors study the aerodynamic efficiency of a variety of airfoils with different thickness and camber settings. Their lift and drag coefficients as well as their surface pressure and flow-field characteristic are evaluated. The authors conclude that for Reynolds below $10^6$, the lift and drag characteristics cannot be assumed as constant. It is shown that when the Reynolds number of the flow falls below $10^5$, the laminar separation bubble grows in size reaching a diameter of between 15 and 40 percent of the chord length, while gradually moving toward the trailing edge, which causes early stall at lower angles of attack. The turbulent boundary-layer is shown to increase its thickness, which results in the increase of the airfoil profile drag.

In [3], the authors show the impact of various geometrical parameters like thickness, camber, chord length, blade twist, taper ratio and rotor solidity, as well as the effect of winglets for different sets of airfoils both symmetrical and non-symmetrical. Shown is an optimum set of parameters for UAV rotor blades for their efficient operation in low-Reynolds flow conditions.

In [4], the authors study the impact of taper and twist, as well as the effects of sharpening of the leading and trailing edges of the blades. In total, 8 rotor configurations are tested for Reynolds of approximately 35000. It is shown that sharpening of the leading and trailing edges of the blades reduces the thickness of the trailing wake and thus lowers the profile drag, which results in a better aerodynamic performance. The negative linear blade-twist is shown to improve the rotor aerodynamic performance [4, 5].

In [5], the authors compare experimental and numerical data for small-sized hovering rotors with highly-twisted and untwisted blades. The experimental data for that study comes from both thrust measurements in steady operational regimes and PIV flow-field measurements. This work reveals the inadequacy of the BEMT, when used for the prediction of the aerodynamic performance of rotors, operating at low-values of the coefficient of thrust and in low-Reynolds flow conditions. It also reveals that in cases of very low thrust settings the highly-twisted blades can become inferior to the untwisted blades in terms of aerodynamic efficiency. This is due to the fact that for the same trust setting, the highly-twisted blades will generate higher inflow and pressure drag, which contributes to the overall profile drag of the rotor.

In [6-8], the authors reveal the importance of geometry optimization as a way to improve the aerodynamic performance at low-Reynolds flow conditions. Those works are an excellent example of complex aerodynamic analysis, which incorporates both numerical and experimental data.

In [9, 10], the authors study the static aerodynamic performance of model helicopter rotors for different sets of blades, angular velocities and pitch settings. In both works the respective authors present in detail the helicopter rotor test stands and the applied methodologies, which permit the evaluation of the aerodynamic performance of the tested hovering rotors. In [10] is shown a methodology for the experimental evaluation of the profile drag of the airfoil of the rotor blades.

From all reviewed works, so far only in [3] the authors show the impact of the variation of the number of blades on the aerodynamic efficiency of the rotor. Apart from [3], there are no other experimental studies, known to the authors of this paper, which evaluate purely the impact of the number of blades on the aerodynamic characteristics of the hovering rotor. The present experimental study aims to reveal that impact by comparing 3 rotor configurations, which have the same Goettingen 417 airfoil, twist setting, taper ratio, chord length, planform and radius. In such a way it is assured that
only the rotor solidity is being altered. A fourth configuration of two-bladed rotor with NACA0012 airfoil is also being tested in order to compare the aerodynamic performance between thin nonsymmetrical and thick symmetrical airfoils at those low-Reynolds flow conditions.

What is even more important in this present experimental work is that by increasing the number of blades in the rotor setup, a more complex variable is being introduced, which is the Blade-Vortex Interaction (BVI). This phenomenon has a complex mathematical predictability, as there are three scenarios for the blade-vortex encounter, depending on whether the vortex emitted by the previous blade is still above, on or below the plane of rotation by the time the following blade of the rotor passes through that same angular position. The BVI is not constant and varies quantitatively with the variation of the angular velocity of the rotor and the pitch angle of the blades. All those uncertainties have motivated the authors to undertake the present experimental study.

2. Experimental setup

Different series of measurements are performed on the specially built helicopter rotor test stand. Figure 1 shows all four rotor configurations that are tested. All four rotor configurations have non-tapered (rectangular) untwisted blades. One of those two-bladed rotor configurations has the NACA0012 airfoil, while the other three have the Goettingen-417 (Goe417) airfoil. All performed experimental tests are static, thus both the speed of rotation of the rotor and the pitch angle of the blades are kept constant. Those parameters are changed incrementally between each test sessions, as described in section 3. Experimental Methodology.

![Figure 1. Helicopter rotor test stand with all 4 rotor configurations.](image)

2.1. Test stand description

Figure 1 shows the helicopter rotor test stand, which allows for the possibility to measure the rotor thrust $T$, N, the torque $Q$, Nm and the angular speed of rotation $\Omega$, rad/s. The stand is equipped with the following measuring devices:
• Torque transducer HBM T20WN with nominal (rated) torque of 1 Nm, accuracy class 0.2 and output voltage ±10 V.
• Force transducer HBM S2M with nominal (rated) force of 10 N, accuracy class 0.02 and output voltage of 2 mV/V.

The tested rotor is driven with a brushless electric motor Maxon ECi-40 with nominal power of 100 W. It allows for rotational speeds of up to 4190 RPM. The electric motor has an in-built Hall sensor, which allows for measurement of the rotational speed. The motor is driven with Maxon ESCON 50/5 servo controller, which permits precise regulation of the rotational speed.

The pitch angle of the blades is varied with a spindle-driven mechanism Maxon GP22S with a gear ratio of 1:370. The spindle is driven by the EC-22 electric motor with nominal power of 40 W.

The electric motors are controlled automatically according to a programmed test schedule. This allows for multiple operational regimes to be evaluated in one test session without the need to constantly stop, re-adjust and re-start of the test stand.

The data acquisition from the force and torque transducers is ensured by the HBM PMX measuring amplifier system, shown in figure 2. The data acquisition system allows for the automatic gathering of all measured experimental data, which is stored in a well-structured database.

![PMX Measuring Amplifier System](image)

**Figure 2.** Helicopter rotor test stand setup.

3. Experimental Methodology

The experimental study is performed as follows: for each test session for all four rotor configurations the pitch angle $\theta$, deg is set from 2 deg to 16 deg with an increment of 2 deg, while the speed of rotation of the rotor is varied from 500 RPM up to 1700 RPM with an increment of 100 RPM. Each test session is repeated 10 times and the results are averaged. Additionally, for all four rotor configurations, a study of the profile drag at zero thrust is performed. For that purpose, for each speed of rotation the pitch angle of the blades is varied until the thrust of the rotor $T=0$ N is equal to zero. Thus, the torque at zero thrust $Q_0$, Nm is obtained. After that, all blades are removed, in order to measure the no blades torque $Q_{nb}$, Nm. Then, the torque due to profile drag $Q_{pd}$, Nm can be obtained by subtracting $Q_{nb}$ from $Q_0$. If $Q_{pd}$ is multiplied by the angular speed of rotation $\Omega$ that gives the power consumption due to profile drag $P_{pd}$, W.

The coefficient of profile drag $C_{pd}$ can be computed with (1):

$$C_{pd} = \frac{(Q_0 - Q_{nb})\Omega}{\rho A \Omega R^3} = \frac{Q_{pd}\Omega}{\rho A V_{tip}^2} = \frac{P_{pd}}{\rho A V_{tip}^2},$$

where $\rho$ is the air density, kg/m$^3$; $A=\pi R^2$, m$^2$ is the area of the rotor; $R$, m is the radius of the rotor; $V_{tip}=\Omega R$, m/s is the tip speed of the blades.

The rotor solidity $\sigma$ [11] is obtained with (2):
\[ \sigma = \frac{N_b c}{\pi R}, \]  
(2)

where \( N_b \) is the number of blades of the rotor configuration and \( c, \) \( m \) is the blade chord.

The coefficient of profile drag at zero thrust \( C_{D0} \) \([12]\) is derived with (3):

\[ C_{D0} = \frac{8c}{\sigma}. \]  
(3)

The coefficient of thrust of the rotor \( C_T \) \([11]\) is computed with (4):

\[ C_T = \frac{T}{\rho A \Omega^2 R^2}. \]  
(4)

The coefficient of thrust of the rotor \( C_P \) \([11]\) is obtained with (5):

\[ C_P = \frac{Q}{\rho A \Omega^2 R^2}. \]  
(5)

The coefficient of thrust of the rotor \( FM \) \([11]\) is derived with (6):

\[ FM = \frac{C_T^{3/2}}{\sqrt{2}C_P}. \]  
(6)

The Figure of Merit computed with (6) is shown to have been introduced as a nondimensional measure of hovering efficiency for helicopter rotors, which provides a common base for comparison between rotors with different geometries.

In order to ensure comparability between the results for helicopter rotors with different number of blades and thus with different rotor solidity, the following dimensionless parameters are used:

- \( C_T/\sigma \) – blade loading coefficient,
- \( C_P/\sigma \) – power coefficient.

The coefficient of lift of the rotor \( C_{Lr} \) is computed with (7):

\[ C_{Lr} = \frac{2T}{\rho (0.7 \Omega R)^2 S}, \]  
(7)

where \( S = N_b c, m^2 \) is the total area of all blades of the rotor.

The coefficient of drag of the rotor \( C_{Dr} \) is obtained with (8):

\[ C_{Dr} = \frac{2 \left[ Q / (0.7 \Omega R) \right]}{\rho (0.7 \Omega R)^2 S}, \]  
(8)

### 4. Results and discussions

Figure 3 presents the variation of the coefficient of profile drag at zero thrust \( C_{D0} \) from the Reynolds number of the flow for all 4 rotor configurations. It can be observed that Goe417 airfoil has a lower profile drag compared to NACA0012, which is expected as the latter airfoil has a two times higher relative thickness. It can be seen that as the number of blades increases the profile drag increases too.

This can be contributed to the more frequent blade-vortex encounters, as with larger number of blades there are more BVIs, which alter the inflow distribution along the radius of the blades and especially at the tip part. That results in a redistribution of the effective angle of attack along the blades, which alters the zones with positive and negative thrust contribution, all within the total sum of zero rotor thrust. PIV experimental studies will be performed with the same rotors, in order to confirm that observation.

Figure 4 shows the hover polar for all tested rotor configurations for Reynolds number of approximately 42000. As expected, lower disk loading of the rotor achieves better hovering efficiency. Thus, the four-bladed rotor configuration requires the least power for each produced unit of thrust. It can be seen that for very low values of the blade loading coefficients the two-bladed rotor with NACA0012 airfoil has superior hovering efficiency. However, at those low power setting there are no practical helicopters or rotary-wing UAVs, which will attempt to perform hover.
Figure 3. Variation of profile drag with Reynolds.

Figure 4. Hover polar for all tested rotor configurations for Re≈42000.

Figure 5 presents the dependency of the Figure of Merit on the blade loading coefficient for all 4 rotor configurations. The larger rotor solidity allows for higher power loading settings of the rotor before reaching stall conditions. That is why a larger number of blades allow for a higher value of the Figure of Merit. The two-bladed rotor with Geo417 airfoil is superior to the one with NACA0012 airfoil at those low-Reynolds flow conditions.

Figure 5. Figure of Merit against the blade loading coefficient for all 4 rotors for Re≈42000.

Figure 6. Rotor aerodynamic efficiency in hover for all 4 configurations for Re≈42000.

On figure 6 is shown the aerodynamic quality of the blades of the rotor against the Figure of Merit for all 4 tested configurations. Those results clearly show that rotors having blades with higher aerodynamic quality can achieve better hover efficiency. It can be noticed that a larger number of blades and hence rotor solidity, allows for a broader operational range at maximum aerodynamic efficiency in hover. For similar hover performance the two-bladed rotor configuration with Geo417 airfoil has a superior aerodynamic quality when compared to the rotor with the thicker symmetrical NACA0012 airfoil.

Figure 7 is presents the aerodynamic polar of the airfoil of the rotor blades for each one of the 4 tested configurations. It seems that as the number of blades is increased, the more frequent BVIs contribute for more favorable pressure redistribution along the radial span of the blades, which results
in a higher overall coefficient of lift of the airfoil. PIV experimental studies have to be performed with the same rotor configurations, in order to obtain a greater insight of this effect.

**Figure 7.** Airfoil aerodynamic polar for all tested configurations for Re≈42000.

**Figure 8.** Figure of Merit against the coefficient of drag for all 4 configurations for Re≈42000.

Figure 8 presents the hover efficiency against the coefficient of drag for all tested rotor configurations. This data representation allows for the evaluation of the amount of generated drag for each rotor configuration in their entire hover operational range. As previously demonstrated, with the increase of the number of blades higher aerodynamic efficiency of the rotor can be achieved. Hence, what can be observed in the case of the three- and four-bladed rotors is that less units of drag are generated for each unit of hover efficiency of the rotor.

5. **Conclusion**

Although the profile drag increases with a larger number of blades, the Goe417 airfoil achieves higher coefficient of lift and hence better aerodynamic quality in both the three- and four-bladed configurations, when compared with the two-bladed rotor.

By increasing the rotor solidity with a larger number of blades, the rotor achieves better aerodynamic and hover efficiency, generating more lift and less overall drag for identical operational regimes.

The three- and four-bladed rotor configurations require less power for each produced unit of thrust, when compared to the two-bladed rotor, as a lower disk loading of the rotor achieves higher hovering efficiency.

A larger number of blades and hence rotor solidity, allows for a broader operational range at maximum aerodynamic efficiency in hover.

Rotors, having blades with better aerodynamic quality, can achieve better hover efficiency.

PIV flow-field measurements have to be performed in order to fully study the nature of the BVIs for those low-Reynolds ranges.

**Acknowledgements**

This work was supported by the European Regional Development Fund within the Operational Program “Science and Education for Smart Growth 2014 - 2020” under the Project CoE “National center of mechatronics and clean technologies” BG05M2OP001-1.001-0008.

**References**

[1] Carpenter P J 1958 Lift and Profile-drag Characteristics of an NACA 0012 Airfoil Section as Derived from Measured Helicopter-rotor Hovering Performance NACA TN 4357
[2] Winslow J, Otsuka H, Govindarajan B and Chopra I 2018 Basic understanding of airfoil characteristics at low Reynolds numbers *Journal of Aircraft* **55**(3) pp 1050–61

[3] Benedict M, Winslow J, Hasnain Z and Chopra I 2015 Experimental investigation of micro air vehicle scale helicopter rotor in hover *Int. J. of Micro Air Vehicles* pp 231–55

[4] Ramasamy M, Johnson B and Leishman J G 2008 Understanding the aerodynamic efficiency of a hovering micro-rotor *Journal of the American Helicopter Society* **53**(4) pp 412–28

[5] Ramasamy M, Gold N P and Bhagwat M J 2010 Rotor hover performance and flowfield measurements with untwisted and highly-twisted blades *36th European Rotorcraft Forum* **1** pp 770–84

[6] Hnidka J, Rozehnal D and Maňas K 2020 Optimization of SUAV’s propeller in a hover *MATEC Web Conf.* **313** 00045

[7] Hnidka J and Rozehnal D 2019 Calculation of the maximum endurance of a small unmanned aerial vehicle in a hover *IOP Conf. Ser.: Mater. Sci. Eng.* **664** 012002

[8] Kądrowski D, Kulak M, Lipian M, Stępień M, Baszczyński P, Zawadzki K and Karczewski M 2018 Challenging low Reynolds - SWT blade aerodynamics *MATEC Web Conf.* **234** 01004

[9] Lee B, Byun Y, Kim J and Kang B 2011 Experimental hover performance evaluation on a small-scale rotor using a rotor test stand *Journal of Mech. Science and Technology* **25**(6) pp 1449–56

[10] Panayotov F, Dobrev I, Massouh F, and Todorov M 2018 Experimental study of a helicopter rotor model in hover *MATEC Web of conf.* **234** 01002

[11] Leishman J G 2006 *Principles of Helicopter Aerodynamics* (Cambridge University Press) chapter 2 p 69