Transactions on Aerospace Research eISSN 2545-2835, VOL. 271, NO. 2/2023, 17-24
DOI: 10.2478/tar-2023-0008

ULTRALIGHT AND VERY LIGHT HELICOPTER ROTOR DATA

Vitaly Dudnik*[1,2] and **Victor Karabut**[2]
[1] Silesian University of Technology, Akademicka 2A, 44-100 Gliwice, Poland
[2] RS Helikopter GmbH, Brienner Str. 7 80333, München, Bayern, Germany

Abstract
In recent years, a significant number of one- and two-seat lightweight helicopters have come into existence, and this makes it possible to analyse parameters and determine dependencies for this class of helicopters. The knowledge of such dependencies is necessary at the preliminary design stage. The analysis performed in this paper and its comparison with the statistical data of all categories of helicopters made it possible to determine the necessary corrections in the methods of determining the parameters of the helicopter's rotor systems.

Keywords: ultralight helicopter, main rotor, blade, preliminary design
Type of the work: research article

Nomenclature

C	– chord, m
C_t	– rotor thrust coefficient
D	– main rotor diameter, m
DL	– disc loading, Pa
g	– acceleration due to gravity, m/s^2
m_0	– maximum take-off mass or weight (MTOM or MTOW), kg
N_b	– number of blades
R	– rotor radius, m
μ	– advance ratio
π	– Pi number
σ	– rotor solidity
ΩR	– blade tip speed, m/s

1. INTRODUCTION

A lightweight helicopter that takes off near the house is the most convenient vehicle for personal use, and that is why customers have been interested in such aircraft for a long period of time. Due to improvements in recent technology, one- and two-seater helicopters have become more compact and lightweight. Examples of such helicopters are shown in Fig. 1. According to the European classification, such rotorcraft belong to the category of ultralight and very light helicopters. The airworthiness standards

* Corresponding Author: vvdudnik812@gmail.com
ARTICLE HISTORY **Received** 2022-10-28 **Revised** 2023-01-12 **Accepted** 2023-03-02

of ultralight helicopters are normalised by national governments, but the standards for the Very light class are established by the EASA. Separate requirements that are not similar to requirements applied to light helicopters are due to the lower level of the potential danger of these classes of helicopters. The limitations of a take-off mass of Ultralight and Very light rotorcraft limit their kinetic energy and make them safer than other aircraft for people and the environment. This explains why certification methods have been simplified and liberal flight rules requirements are introduced for these classes of aircraft. In the last 25years, there has been a significant increase in the amount of new ultralight and very light helicopters. This fact makes it possible to conduct a statistical analysis of their parameters. A total of 34 serially produced and experimental helicopters with a maximal take-off mass from 260 kg to 730 kg were analysed during this research study. Complete statistical data were not collected for all rotorcraft, but the collected data are sufficient enough to determine the tendency of development of rotor systems of light helicopters.

There are two trends for light helicopters' preliminary design to be considered. On the one hand, they should obey the laws of mechanics and, accordingly, the general rules of helicopter design, and on the other hand, the scale factor should have a significant effect on such small-size rotorcraft. According to this, it is important to compare functional dependencies of helicopter's parameters with dependencies that were determined on the basis of processing the statistical data for all weight categories rotorcraft. Such an analysis is needed for specialists who are responsible for the preliminary design stage in the development of small helicopters. The rotor system is the base of the helicopter; so, it was selected for initial analysis.

The most convenient approximation of statistical data for all classes of helicopters was given in paper [1]. Due to this fact, the main part of comparisons of statistical data of light helicopters with general tendencies was done with the use of dependencies which are given in the above-mentioned paper.

A B

Figure 1. The small weighted helicopter. (A) Single-rotor helicopter Ranabot CH-77 (Italy), MTOM-500 kg, (B) coaxial helicopter Rotorschmiede VA-250 (Germany), MTOM-500 kg.

1.1. Geometrical parameters of the main rotor

Disc loading is one of the most important parameters of the helicopter's main rotor. This parameter affects flight dynamics and other characteristics. As a rule, a decrease in this load not only leads to the growth of the relative lifting capacity in the hovering flight but also increases the rotorcraft's stability to wind gusts, and it also gives it the ability to use smaller hangars for parking the helicopter. The existing practice in helicopter design shows that the value of disc loading changes in relation to the mass of the helicopter. The value of disc loading for some of the heavy helicopters can be up to 700 Pa. However, the lightest rotorcraft have the lowest value of disc loading, which is about 100–170 Pa. For big rotorcraft, there is also a dependence of disc loading on maximum flight speed. The value of maximum speed for small helicopters changes within a small range, and that is the reason why speed can't be used as a parameter for disc loading correlation. The data of the existing single-rotor and coaxial helicopters are given in Fig. 2. Disc loading for coaxial rotors was calculated with disc loading of an equivalent single rotor with doubled rotor solidity. Presented data show that coaxial helicopters have a greater value of disc loading; so, it means that data for the main rotor can be approximated separately for coaxial and single-rotor helicopters. It can be seen that a row of helicopters has an identical mass and is located at the mark of 450 kg. This is explained due to historical circumstances—the border of the ultralight class of aircraft was fixed at this mark for a long time in Europe; so, many aircraft limited their mass characteristic on this level. Currently, the rules and laws in some countries have changed; so, this limit won't be observed in the coming years.

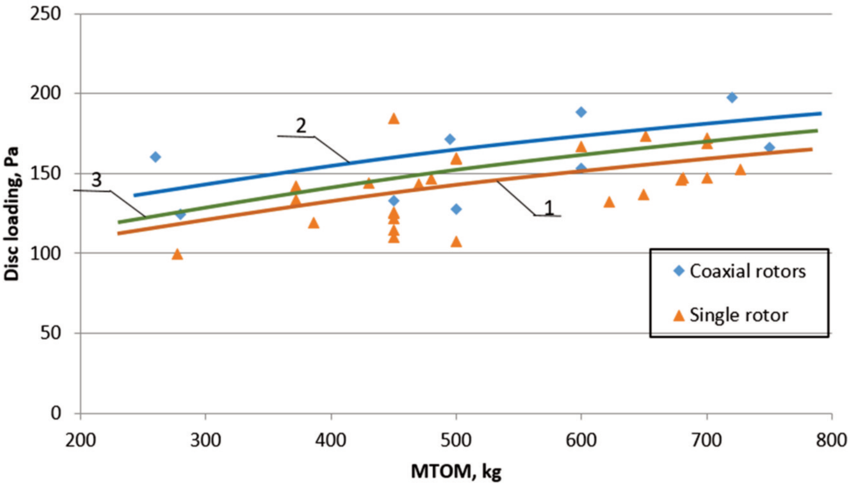

Figure 2. Dependence of discs loading on MTOM (1 – approximation curve for single rotor helicopters, 2 – approximation curve for coaxial helicopters, 3 – disc loading dependence according to [1]).

It should be noted that the two rotorcraft discussed here make use a common trend. Both of them were pioneers of the new generation of small helicopter design. Particularly, the high value of disc loading hasa single-rotor helicopter – M80 Masquito (not Mosquito XE) and coaxial Berkut-SL. For the first one, it seems that the designers didn't have enough design statistics and experience for the development of the light helicopters, as a result of which they used the main rotor with a small diameter. As for the second one, the rotorcrafthad more weight than expected. Particularly, it had three gearboxes. Both of these helicopters are serially not currently produced.

The dependence of the disc loading on the MTOM in the 1/3 degree is justified in papers [1,2,3]. At the same time, the proposed approach of taking into account only the exponential dependence for light helicopters [3] gives a significant error. At the same time, the dependence proposed in [1] that considers additional components (curve 3, Fig. 2) shows a good relation between the average load of coaxial and single-rotor helicopters. However, it is better to take into account such rotor schemes in the calculations. According to this, the approximation functions will be defined as follows:

single-rotor helicopters (curve 1, Fig. 2)

$$DL = 18.68 m_0^{1/3} - 6.44 \quad (1)$$

coaxial helicopters (curve 2, Fig. 2)

$$DL = 18.45 m_0^{1/3} + 18.12 \quad (2)$$

The data of rotor diameters and curves from MTOM are presented in Fig. 3. These data on disc loading were calculated according to the relation shown in Eqn (3):

$$D = 2\sqrt{\frac{m_0 g}{\pi DL}} \tag{3}$$

It's interesting to see that the curve of the main rotor diameters which was approximated for data of single-rotor helicopters for all weight categories [1] (curve 3, Fig. 3) shows lesser values of rotor diameters, which are comparable with diameters of coaxial light helicopters. Moreover, it has a gentle slope. This difference shows that even though all the helicopters obey the common trends, the approximated curves will have breaks with the next increase of MTOM. The different slopes of the curves for light helicopters and heavier rotorcraft can be explained by the required speed of big helicopters for efficient transport operations. The speed of small helicopters is just about the same level for all rotorcraft, and designers often work on increasing the load capacity while considering speed as a less important factor.

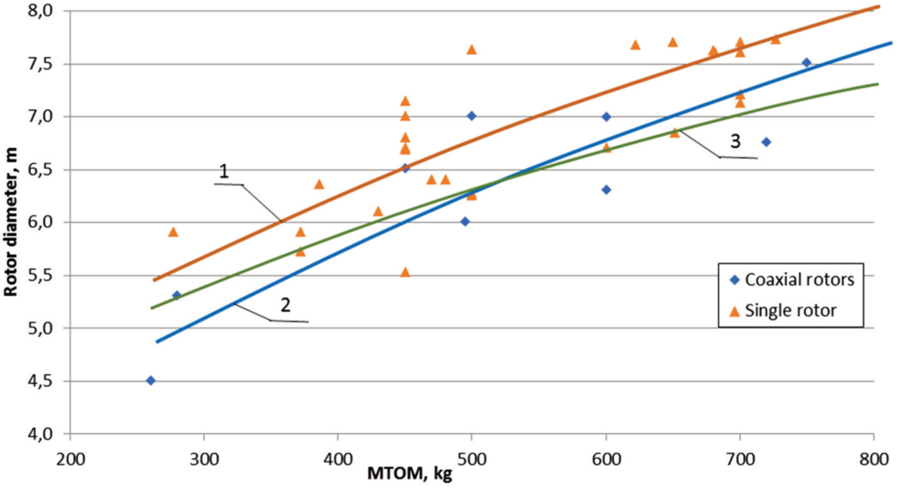

Figure 3. Dependence of the main rotor diameter on MTOM (1 – approximation curve for single rotor helicopters, 2 – approximation curve for coaxial helicopters, 3 – rotor dependence according to [1]).

The main rotor blade section of little helicopters, as a rule, has a relative thickness of 12%–15%. This value is more than the value for helicopters with bigger take-off mass, which often have tip chords about 8%–10% of the thickness. Such difference is in small speeds of the horizontal flight of the one and two-seat rotorcraft. The main rotor chord more clearly depends on MTOM and blade number. The increase in blade quantity leads to chord reduction. It should be noted that almost all ultralight and very light helicopters have two-bladed main rotors with a common teeter hinge. Only three helicopters are equipped with the three-bladed main rotors. Such rotors are more difficult to construct and take up more parking space because of the impossibility to set blades in the longitudinal direction of the aircraft, which decreases the transverse size. The total cost increases with the price of one blade. However, these rotors also have advantages. The rotor disc becomes more compact, and the level of vibration is reduced. Specifically, the reduction of the level of vibration could be sensitive for single-rotor helicopters. A somewhat better situation could be for two-blade coaxial helicopters. The azimuth of the interference of those rotors could be set in a position where the oscillations of the blades will be in the counter phase. As a result, the vibration could be reduced up to 1.5–2 times in the most characteristic airspeed range of the flight.

As stated above, only three low-mass helicopters have three-bladed rotors. Of course, it is impossible to determine the behaviour of functions based on three parameters; so, a parallel dependence on two-bladed rotors was used to construct the dependence curve for three-bladed rotors.

Chord statistical data and approximation functions for small helicopters are shown in Fig. 4 (curves 1 and 2). Functions for all masses of helicopters [1] are shown in the same figure (curves 3 and 4). It can be seen that, despite common similar tendencies, the parameters of the small rotors have a difference in general dependencies [1–8]. The chord value increases slower than the mass for little rotorcraft. The two-bladed rotors could be approximated by the following relation:

$$C = 0.0619\frac{m_0^{0.226}}{N_b^{0.426}} \quad (4)$$

It should be noted that the aspect ratio of blades of small rotorcraft is in the range of 14–23, which is within the limits typical for helicopters of heavier classes [6].

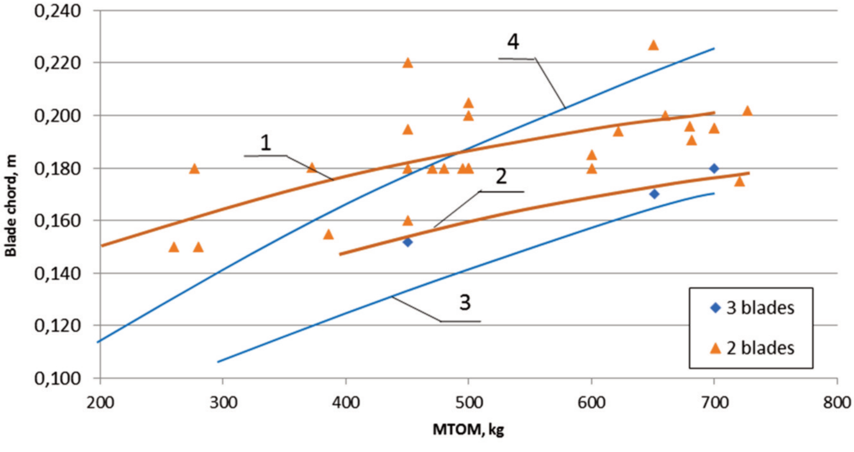

Figure 4. Dependence of the blade chord on MTOM (1 – approximation curve for two-bladed rotors, 2 – approximation curve for three-bladed rotors, 3 – approximation curve for three-bladed rotors according to [1] 4 – approximation curve for two-bladed rotors according to [1]).

The rotor solidity is also one of the important parameters of the main rotor. Often, the small value of this parameter increases the performance of the helicopter in the hover flight mode, but at the same time, its value should be large enough for it to fly in conditions of maximum air speed and altitudes of the dynamic ceiling for this rotorcraft. Generally, the solidity of the rotor increases as the mass of the helicopter increases, but this common tendency has the bouncing structure, which is sharply increased while changing the number of blades. Taking into account that an absolute number of light helicopters have two-bladed main rotors, the reverse situation could be established that solidity is decreased when the mass of the helicopter is increased (curve 1 Fig. 5). The scale factor is the main reason why solidity increases while the mass of the helicopter decreases. Particularly, it’s difficult to produce a technological rotor blade with the required center of mass position for the small dimensional main rotor.

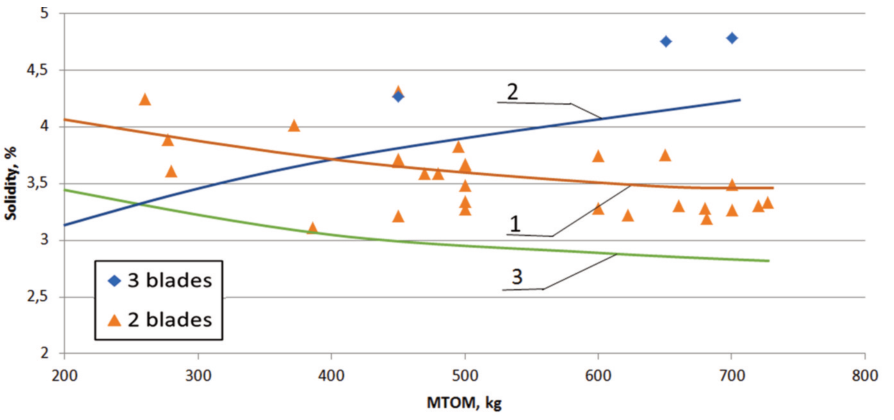

Figure 5. Dependence of the rotor solidity on MTOM (1 – approximation curve for two-bladed rotors, 2 – approximation curve according to [1], 3 – the minimum value of the rotor solidity according to [3]).

The minimum value of rotor solidity, which is the reason flights perform without stall on the tip of the retreating blade, should be used according to the method mentioned elsewhere [3,4,5]. The flight in conditions of maximum speed or maximum altitude is considered. The stall limit is estimated based on the limit value of the ratio $(C_t/\sigma)_{lim}$. It should be noted that the parameters of the maximum speed of flight in relation to the tip speed of the rotor are almost independent of the masses in the range of light helicopters and are in the very narrow range of μ = 0.2–0.3 (Fig. 6). For example, the limit ratio $(C_t/\sigma)_{lim}$ for such μ is in the range of 0.18–0.22 according to [3]. In the case of maximum value of $(C_t/\sigma)_{lim}$ = 0.22, the limit value of the rotor solidity is minimal and parallel to the approximation curve which is characterised for two-bladed rotors (curve 3, Fig. 4), and all the small helicopters are in the right area. The solidity limit function is the same as that of statistical curve 1 (Fig. 5) when the minimum value of $(C_t/\sigma)_{lim}$ = 0.18. This indicates that the limit criteria of the absence of stall for retreating blade dominate the design procedure of light helicopters.

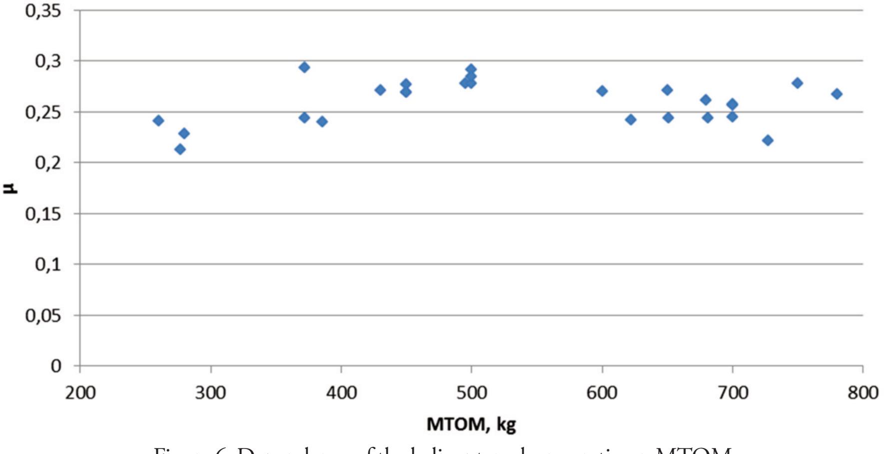

Figure 6. Dependence of the helicopter advance ratio on MTOM.

1.2. Tip speed of the main rotors

As known, the tip speed of the main rotor depends on rotor sizes and flight speed. Classically, the value of tip speed for helicopters is about 180–230 m/s [3,4,5,6]. But the main part of small helicopters has less tip speed even up to 150 m/s. Most often, these small values of the tip speed allow to get a good thrust performance for rotors in the hovering flight mode that fly at low speeds. Besides this, low tip speeds generate lower vortex noise, and the noise of periodic processes has an infrasound frequency of less than 20 Hz, which the human ear cannot hear. Manufacturers compensate for the low tip speed by increasing the weight of transmission and blades.

The flight airspeed almost has no influence on the choice of tip speed, taking into account the fact that the airspeed of light helicopters is little and their parameters are far from wave crisis. The tip speed data show that they depend on the rotor diameter, and this dependence is almost linear (curve 1, Fig. 7). The total exponential dependence, which is given in [1], for all helicopters (curve 2) slopes gently real statistical data for light helicopters. At the same time, a significant error is observed for the smaller rotors. In this regard, it is possible to use the upgraded exponential dependence for small-sized helicopters, described by the following expression:

$$\Omega R = 57.967 D^{0.6149} \tag{5}$$

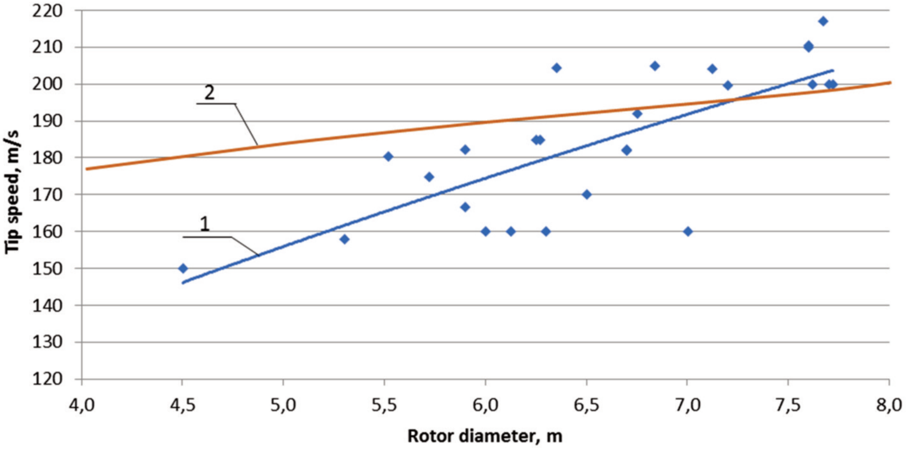

Figure 7. Dependence of the blade tip speed on rotor diameter (1 – approximation curve, 2 – rotor dependence according to [1]).

CONCLUSION

Analysis of main rotors parameters shows that the general tendencies, which are specific for the main rotors of heavyweight helicopters, also apply to light rotorcraft. However, there are a number of features that should be considered during the preliminary design stage. These features are due to the fact that small helicopters don't have significant flight speeds, the tip speeds of these helicopters are lower as the blades are far from wave crisis and the rotor solidity also has a lesser value. The scale factor has an influence on almost all parameters. The statistical parameters and relations presented in this paper could be useful for designers that work at the preliminary design stage of light helicopters.

REFERENCES

[1] Rand, O. and Khromov, V. Helicopter Sizing by Statistics. *American Helicopter Society*, *58th Annual Forum*. Montreal, Canada (2002).

[2] Raymer, D. *Aircraft Design*: *A Conceptual Approach*, 3rd ed. American Institute of Aeronautics and Astronautics, Inc., Reston, Virginia (1999).

[3] Fradenburg, E. "The First 50 Years Were Fine But What Should we do for an Encore? Alexander A. Nicolsky Lecture." *Journal of American Helicopter Society* (1994). p.3–20.

[4] Krenik, A. and Weiand, P. *Aspects on Conceptual and Preliminary Helicopter Design*. Deutscher Luft- und Raumfahrtkongress, Document 420207 (2016).

[5] Losev, L. Preliminary Determination of The Helicopter General Parameters Under Criteria of Take-off Mass Minimum. Kharkov Aviation Institute, Kharkov (1988).

[6] Losev, L. and Ryabkov, V. *Choice of The Coaxial Helicopter Parameters Under Criteria of Take-off Mass Minimum*, Kharkov Aviation Institute, Kharkov (1999).

[7] Tishchenko, M. *Choice of The Helicopter Parameters At The Preliminary Stage of Design*. Moscow Aviation Institute, Moscow (2010).

[8] Johnson, W. *Design and Analysis of Rotorcraft*. NASA/TP—2015–218751, NACA, Ames Research Center, (2015).

[9] Xin-Lai, L., Hu, L., Gang-Lin, W., and Zhe, W. "Helicopter Sizing Based on Genetic Algorithm Optimized Neural Network, Chinese." *Journal of Aeronautics* Vol. 19 No. 3 (2006). p. 212–218.