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Review of Modern Helicopter Constructions and an Outline of Rotorcraft Design Parameters

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Abstract. This work contains the results of a modern helicopter construction analysis. It includes the comparison of almost seventy rotorcraft constructions in terms of size in line with EASA requirements – large and small helicopters. The helicopters are also divided because of a mission purpose. The proposed division for large aircrafts is: transport, multipurpose, attack and for small aircrafts: observation, training, and utility. The aircraft construction features are described. Average dimension values of airframes and rotors are shown. Helicopter rotor arrangements are presented in terms of an operational purpose. Next, the rotorcraft design inputs are described. The mathematical formulas for design inputs are given. The ratios are calculated and gathered for the compared aircrafts. Correlation between the analysed parameters is presented on charts. Design inputs are also presented in the paper as a function of MTOW. The function trends are determined to provide an evaluation tool for helicopter designers. In addition, the parameters are presented as possible optimisation variables.
Keywords: aerospace, helicopter, analysis, rotor, military

1. INTRODUCTION

The modern battlefield, according to [1], requires the armed forces to use new technologies and to introduce solutions that will be astonishing for a potential opponent. One of the most important branches of today's warfare are air operations. One of the types of air operations is the support of land and naval actions. The backing can be realised by providing troops with transport, firing, radiolocation, observation and more of what is needed to conduct the operations properly. One of the best aircrafts, to grant all of the mentioned duties, are the rotorcrafts. The helicopters, because of their vertical lift ability and capability to dynamically change their position about all three movement axes and about all three rotational axes, can serve in changeable environment conditions and can adapt to new mission challenges.

From the operational needs there come the prerequisites for a helicopter construction. As it is described in [2], from those conditions there come the first parameters like: payload, speed, range, size etc., everything that is needed to fulfil the mission terms. However, there are some rigid design rules (mechanics, aerodynamics etc.) that depend on a chosen aircraft and its aeronautical arrangement. Taking into consideration reference [3], there are some crucial requirements that an engineer is obliged to consider in planning a new helicopter: external loads, strength and stiffness, durability and reliability, crash safety, manufacturing and maintenance technology. All of the requirements are inputs to start the design process. The conceptual design phase is described by the Design Wheel.

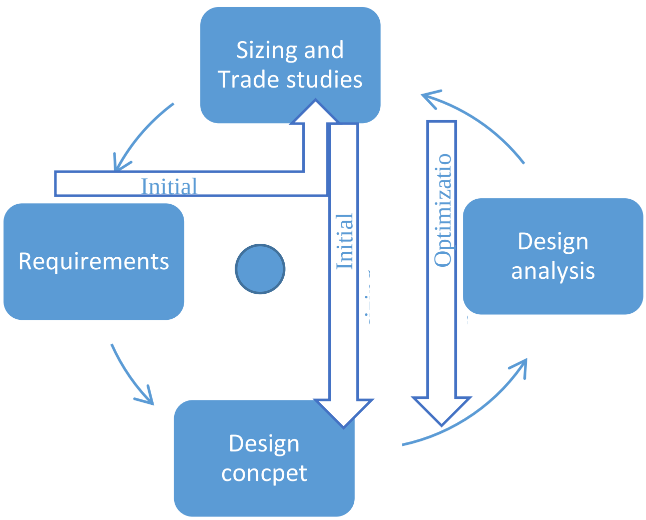

Fig. 1. Design wheel[1]

[1] Adopted from [28].

What needs to be mentioned, because of the subject of analysis, the second source of aircraft requirements comes from legislation – where some design boundaries for civilian or military constructs are enclosed. For example, the civilian helicopters' requirements are described in EASA[2] CS-27 [4] and CS-29 [5]. To adopt this specification to the military environment, EMAR[3] 21 [6] was provided by EDA[4]. The certification specifications point out the requirements for: flight conditions, strength, design and construction, powerplant, equipment and operating limitations. These regulations divide the rotorcraft population into two types: small rotorcraft and large rotorcraft. In this kind of division, the helicopters are catalogued according to their mass and seating capacity.

Because of the described issue, in the next chapter, basing on the EASA's specification, the helicopters' destiny division is proposed. The construction review according to the purpose of the use, will enable to outline the operational problems that were noted during different helicopters' lifecycles.

2. REVIEW OF CURRENT HELICOPTER CONSTRUCTIONS

2.1. Type of the construction because of operating purpose

Because of versatile helicopters usage [7], the manufacturers prepare rotorcrafts' airframes that can be developed into various versions of the same type of aircraft. The modern helicopter frame is prepared for modular replacement of most of the components because of configuration change, or to put in some parts that were improved during an aircraft's lifecycle, for example engines or avionics. However, depending on the mission profile, the basic helicopter construction will be different. As a consequence, some construction division can be proposed:

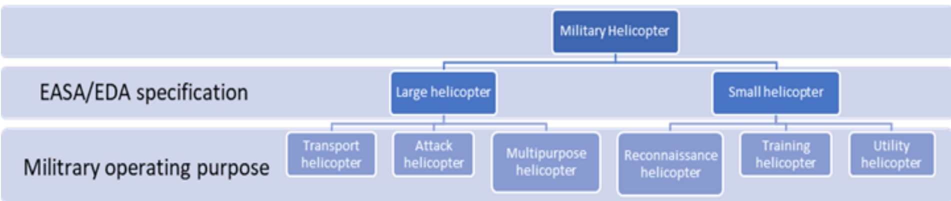

Fig. 2. Helicopter construction classification

[2] European Union Aviation Safety Agency.
[3] European Military Airworthiness Requirements.
[4] European Defence Agency.

The classification, described above, is based on military system requirements and mission effectiveness which are described in [8]. The mentioned conditions determine the performance. While conducting the assigned mission, the helicopter should reach the required level of airspeed, range, and payload. Moreover, a capacity to carry weaponing and resistance to firing may be needed. As it was described in the introduction, these demands determine the rotorcraft construction.

EASA/EDA specification

The EASA legislations regulate the parameters that a helicopter construction must fulfil to be certified [4], [5]. The specifications are broken into subparts which detail the flight, strength, design and construction, powerplant, equipment, operating limitations conditions. For military aircrafts, as stated in EMAR 21 [9], a national law (similar to EASA) is needed to be passed. In accordance with mentioned rules, two main construction categories can be defined. The requirements are also divided into categories which specify certification demands depending on the operation.

Table 1. EASA's helicopter classification

Type	Category	Maximum weight [kg]	Max. seating capacity
Small helicopter	A	≤ 3175	≤ 9
Large helicopter	A	≥ 9072	≥ 10
Large helicopter	B (with category A subparts – C, D, E and F)	> 9072	≤ 10
Large helicopter	B (with category A requirements CS.29.67(a)(2), 29.87, 29.1517 and subparts – C, D, E and F)	≤ 9072	≥ 10
Large helicopter	B	≤ 9072	≤ 10

Rotors' configuration

Before describing the types of military helicopters' construction, it is very important to outline the rotor arrangement of helicopters, the analysis is based on [10]-[12]. The configuration of rotors is determined by the arising torque. The mentioned torque is a consequence of the main rotor's work. The main rotor during flight is acting on the fuselage and generates a reaction moment, which is responding in the opposite direction. To balance the torque and to provide a steady flight, a counter-force is needed. It is realised by an additional rotor/rotors. Three rotors arrangements, which are generally used on military helicopters, are described below. The arrangements are basically independent from the helicopter operating purpose and they can be applied to all of the military types. However, some forms are more likely applicable to certain sorts of construction.

The most popular helicopter rotors' configuration is the Sikorsky configuration with a single main rotor and a small supporting rotor to produce the balancing torque and to control the yaw. Usually, the tail rotor is placed at the end of a tail boom. The auxiliary rotor is set vertically to generate the balancing thrust that acts on an arm about the main rotor axis. In this configuration, the main rotor grants lift, propulsion force, roll and pitch control. This layout is adopted to all kinds of military helicopter constructions. For example, a Polish military multirole helicopter W-3 "Sokol" (Fig. 3) is a typical example of the Sikorsky layout.

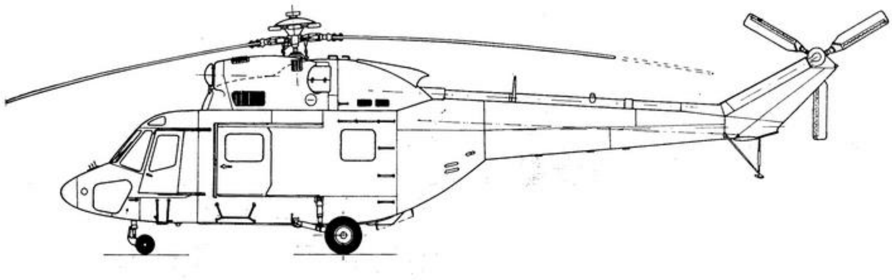

Fig. 3. W-3 "Sokol" – single rotor helicopter layout [5]

The second kind of helicopter aerodynamic arrangement is a construction with twin main rotors, this kind of arrangement is well described in [13]. These elements are the same size and loadings, however, they are rotating in opposite directions. As a consequence, the torques produced by the rotors are naturally balancing themselves. The yaw control is gained by contrasting lateral inclination of the rotors' thrusts. The power of the main rotors is not diminished by an additional smaller rotor. The most popular displacement of the rotors on the construction is the fore and aft configuration, however, there are some constructions which were designed with the side-by-side configuration. Nowadays, they are especially used in constructions with tilted rotors. The twin rotor layout was almost only applied to transport helicopters. The most characteristic representative of twin-rotor helicopters is CH-47 "Chinook" (Fig. 4).

[5] Sketch source: Technika Lotnicza i Astronautyczna.1986 (4-5).

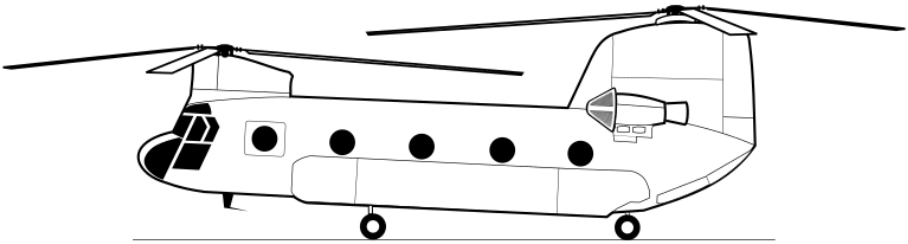

Fig. 4. CH-47 "Chinook" – twin-rotor helicopter layout[6]

The third configuration, which should be described, is a coaxial layout. The international research about this kind of arrangement was summarised in [14]. Coaxial helicopter may be treated as a special kind of a tandem helicopter. No additional tail rotor for balancing the torque is applied, as it was in the twin configuration, the main rotors are compensating each other by rotating in opposite directions. That is why the construction of the helicopter fuselage can be shorter and more compact. Coaxial construction requires rigid rotor blades, and as a consequence, higher, than in the Sikorsky layout, root and shaft bending moments are possible to be tolerated. This gives an opportunity to produce a higher lift force on the advancing and retreating side of the rotors. In the military aircraft it grants a high climb speed and a very high hovering ceiling. The coaxial rotors are mostly used in the Russian helicopter constructions manufactured by "Kamov" company. The representative of a military helicopter with coaxial rotors applied is Ka-52 "Alligator" (Fig. 5).

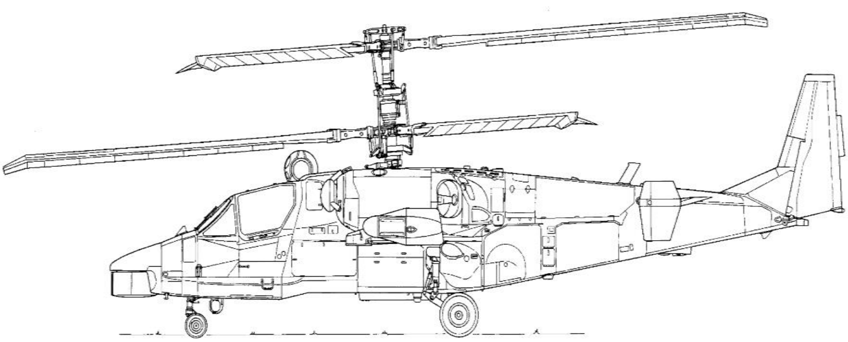

Fig. 5. Ka-52 "Alligator" coaxial-rotor helicopter layout[7]

[6]Sketch source: https://commons.wikimedia.org/wiki/File:CH-47_Chinook_Line_Drawing.svg (last accessed 30.01.2021).

[7] Sketch source: https://www.the-blueprints.com/blueprints/helicopters/kamov/76276/view/kamov_ka-52_alligator_hokum (last accessed 30.01.2021).

Large helicopter

The large military helicopters' family can be divided into three types that determine the rotorcraft elements' construction: transport helicopters, attack helicopters and multipurpose helicopters. These constructions differ in weight, dimensions, equipment and performance. In result the structure of components is also altered.

Transport helicopters conduct supporting missions of military operations. The helicopter tasks in modern warfare are recognised in [15]. Transport helicopters are capable to carry troops, cargo or vehicles. The load can be lifted inside the hold or externally by putting a sling to the prepared attachment point. Transport helicopters are also used for air assault operations, where they are used to deploy troops near the enemy position. In this situation, the high possibility of enemy fire occurs. As a consequence, for transport helicopters' performance, the most important are the payload and the range, next the speed, fire resistance, and survivability. Some transport helicopters are equipped with armament to provide their self-defence.

The described above conditions determine the helicopters' construction. In regard to [16], some features of transport helicopter construction can be indicated. The most important aspect for the vehicle purpose are the dimensions. The main rotor diameter of transport helicopters, according to the rotorcrafts data from [17], is on average of 20 m, however, it depends on the aircraft payload. The heavy lift helicopters have a rotor diameter of 24 m to 34 m. The biggest representative of this group of aircrafts is Mil Mi-26 helicopter (Fig. 6).

Fig. 6. Mi-26 unloading vehicles[8]

[8] Image from the Russian Ministry of Defence.

The fuselage dimensions are on average of 20 m long and of 4.45 m wide. These aircrafts are usually built with two engines, however, some heavy lifts constructions are three-engine. The motors are placed within the upper part of the fuselage, above the cargo hold and crew cabin.

The fuselage is constructed as semimonocoque design. In a transport helicopter it is important to place the bulkheads and the frames in points where internal or external load is going to be attached. These elements are also tasked to concentrate loads. The aircrafts' fuel is usually located underneath the cargo compartment floor, in the bottom part of the hull. The tail rotor diameter, because of a high torque, is proportional to the main rotor diameter and it is wider than in a helicopter with a different operation purpose. The advantage of vertical take-off and landing gives transport helicopters the crucial meaning in tactical operations, rotorcrafts can be used in almost all kinds of terrain conditions to deliver the required cargo. Even when landing is not possible, the load can be deployed in a hovering flight. However, the rotorcrafts' size makes them vulnerable to opponents' detection and fire.

The second type of military helicopters are attack helicopters. According to [18] and [19], these rotorcrafts' primary role is to attack ground targets: infantry, vehicles or fortifications. One of the primary missions of the aircrafts described are close air support operations. In this kind of tasks, attack helicopters are supporting the attack of land forces by heavy fire. Another kind of operations are deep attacks. In deep attacks, helicopters are assigned to precisely destroy the enemy forces that are not in use, however, they can be deployed to operate in the closest time. Because of conducted tasks, these machines are heavily armoured and armed. The aircraft is equipped with cannons, machine guns, rockets or missiles. The most important parameters for the aircrafts' performance are speed and range (flight durability). The velocity is crucial in close fight, it allows the helicopter to avoid being detected and hit. Aircrafts' durability is necessary to allow supporting the operations even when unpredicted circumstances occur.

Construction parameters of helicopters depend on their mission profiles. As it was for transport helicopters, characteristic criterions are the dimensions. The aircrafts' main rotor diameter is on average of 15 m. The fuselage length is quite similar for all of the western constructions and it is on average of 15 m, however, for the Russian attack helicopters they are longer, for example the Mi-28 is 17.5 m long. All attack helicopters are narrow ones. The average fuselage width is 2.25 m. However, the widest Agusta A129 Mangusta is 3.6 m. Rotorcraft minimal size is important to evade the enemy shelling. Decisive is the front narrow shape, it is minimising radar detection and hit opportunity. The special representative of this helicopter family is Kamov Ka-50/52 because of its twin-rotor construction.

The airframe construction is also semimonocoque, however, because of the high possibility of being hit the number of frames and longerons, relative to transport helicopter, is increased. The bulkheads are used for attaching machine guns and cannons. The fittings are needed to be prepared for recoil compensation.

Usually, small wings are attached on the left and right side of the fuselage. Their main purpose is carrying rockets and missiles' launchers, nevertheless, a residual lift force is also produced. On the helicopter's nose, there is a radar mounted, or an observation camera, sometimes a machinegun is placed under the nose section. The engines are installed outside the fuselage on the middle upper left and right side, and the main gear is installed in the hull between them.

Fig. 7. AH-64 attack helicopter[9]

The largest type of military helicopters are the multipurpose (utility) helicopters. In references [20] and [21], these constructions are needed to be available to adjust them to various versions. Utility helicopters are conducting: reconnaissance, attack, transport, medical evacuation, search and rescue or maritime missions. Platform's versatility is the crucial parameter that evaluates the helicopter as a desirable structure. Some aircrafts' versions are prepared by the manufacturer, for example the maritime or search and rescue helicopters, because their equipment, especially radars and cameras, require preparation of electrical installation within the airframe. However, mainly the modern multipurpose airships are made as modular ones. The airframe is prepared to quickly change special equipment and to shape the rotorcraft to a planned mission. This equipment is for example armament, medical equipment, troops' seats or cargo fastening. Depending on a mission profile, some setups can be mounted simultaneously, for example configurations with weaponry and troops' transport. The most characteristic representative of these rotorcrafts' family is UH-60 "Black Hawk".

[9] Image from Boeing official materials.

The multipurpose helicopter's airframe is designed to fulfil all the operational requirements that are defined by the user. As a consequence, the dimensions and the masses of large multi-role aircrafts can be defined somewhere between a transport and a small helicopter. The smallest UH-72A is 10.2 m long and 1.73 m wide with MTOW 3585 kg, on the contrary the H-92 is 17.1 m long and 2.6 m wide with MTOW 12020 kg. However, an average can be specified. For the multipurpose helicopter, the average dimensions are: length of 14.40 m, width of 2.56 m, and a rotor diameter of 15.14 m. The aircraft's proportions are exact to combine all types of an operational purpose. The helicopter's performance is between an attack and a transport helicopter with an average maximum cruise speed of 288 km/h and a range of 700 km. That is 10 km/h less and 100 km more than attack aircrafts, but 10 km/h more and 100 km less than transport aircrafts.

As in all the previously described constructions, the multipurpose rotorcraft airframe is also designed as a semimonocoque structure. A fuselage construction with the number of longerons is more like a transport than an attack helicopter. The longerons and frames are prepared to carry troops or equipment in cargo hold, however, some external fittings are also prepared. The inner structure is arranged with the points where special equipment or passenger seats are safely secured. These points are calculated to carry the loads that came from the mounted devices. Engines and the main gear are placed above the fuselage.

Fig. 8. UH-60M multipurpose helicopter[10]

Small helicopter

With regards to [22] and [23], small military helicopters can be divided into three types of a mission purpose: reconnaissance helicopters, training helicopters and utility helicopters.

[10] Image from Lockhead Martin official materials.

However, most small rotorcrafts are built utility airships that provide all kinds of vertical lift aircrafts missions: transport, evacuation, medical support, reconnaissance, light attack, observation and training. There are only a few constructions that are typically reconnaissance or training rotorcrafts. OH-58D “Kiowa” (Fig. 9) is one of the representatives of observation helicopters. It needs to be added that mostly the observation aircrafts are also lightly armed with guns or missiles. As regards to training machines, the most popular kind of helicopters are Robinsons R22 and R44.

Fig. 9. OH-58D “Kiowa Warrior” reconnaissance helicopter[11]

The small helicopters’ airframes, because of a similar operating purpose, are similar in their constructions. The average fuselage length is of 9.84 m and width is of 1.58 m, where the shortest is the OH-6A with 7.6 m, but its fuselage is the widest with 1.9 m. The narrowest is the prototype CH-14 Aguilucho and the longest is the Bell 429 with 11.73 m. The average maximum cruise speed stays on 252 km/h and it is quite similar for all small helicopters. A range depends on the mission purpose and on assumed load, however, it can be established at 600 km.

The structure of helicopters is designed as semimonocoque, but it differs in some solutions from large helicopters. In this kind of rotorcrafts, the tail boom is more often a pipe which is strengthened with formers and longerons. The popular solving is also using a fenestron instead of a classic tail rotor. The innovative solution is applied on MD Explorer helicopters family, where instead of a tail rotor a NOTAR[12] system is used, the system is well described in [24].

[11]Photo source: https://ghostrecon.fandom.com/wiki/OH-58D_Kiowa?file=OH-58D_Kiowa.jpg, last accessed 12.02.2021.

[12] No tail rotor.

The fuselage is built with frames and longerons, the bulkheads are used to carry the most dangerous loads and loads that come from fittings. Small rotorcrafts are usually single-engine, the rotorcrafts with high MTOW (close to 3175 kg) are twin-engine. In some aircrafts, piston engines are used instead of turbine engines, unlike in large helicopters where only turbine engines are applied. The motors and main gearbox are built upon the fuselage, like it was in the large multipurpose and transport rotorcrafts.

Fig. 10. MD-902 Explorer utility helicopter with NOTAR system[13]

3. COMPARISON OF CONSTRUCTION CHARACTERISTIC PARAMETERS

To compare modern helicopter construction and to outline the dependencies between the design parameters and performance, some characteristics need to be settled. The characteristics will be divided into relative and absolute. The compared absolute qualities are mass, performance and geometry parameters. This correlation is made only to gather and specify some typical features of helicopter types. The most important for further considerations are the relative characteristics. As it is defined in [25], the relative characteristics are calculated ratios, which allow us to measure the influence of main components excellence on aircrafts performance. In the comparison almost seventy modern helicopter constructions were examined.

[13] Image from MD Helicopters official materials.

Absolute parameters

In Table 2 the average main rotor parameters are shown. These statistics are gathered to represent relatives between the rotor geometry and performance. The crucial parameter during the main rotor designing is the blade's tip speed. According to the presented data, the tip speed is similar for all kinds of rotorcrafts. It is a consequence of the fact that the maximum tip's speed is determined by the forward flight conditions. On an advancing blade, the rotor blade speed is summing up with the forward flight speed. Therefore, it appears the possibility of supersonic speed occurrence. According to [26], this phenomenon is a cause of rotor increased noise, vibration and drag. To avoid the undesirable effect, during the conceptual design phase, the main rotor radius and speed are calculated to provide a limited tip velocity. The smaller radius enables us a higher rotor speed implementation. As a result, the overall helicopter performance is mostly constrained by the tip speed. In modern helicopter constructions, the higher rotor velocities are obtained by applying the computer designed blade tip platforms, that postpone the critical Mach number to the higher speeds. The tip shapes are outlined in [27].

Table 2. Absolute main rotor parameters

Helicopter	Average main rotor diameter [m]	Average blade chord [m]	Average rotor speed [rpm]	Average blade tip speed [m/s]
Large	**16.56**	**0.54**	**269.99**	**219.27**
attack	15.22	0.56	275.01	221.01
multipurpose	14.72	0.44	301.20	219.80
transport	22.01	0.64	208.43	217.07
Small	**10.08**	**0.29**	**408.35**	**213.11**
observation	9.62	0.25	412.50	206.71
training	9.90	0.31	409.10	211.29
utility	10.47	0.30	405.33	217.98
Average	**14.24**	**0.43**	**327.91**	**216.69**

Table 3 summarises the comparison of performance parameters for each of helicopters' operational purpose. Some unique features, described in the previous chapter, which came from the operational demands, can be spotted. This summary can also be a base of design inputs, which will fulfil the user needs.

Table 3. Absolute performance parameters

Helicopter	Average MTOW [kg]	Average Rate of climb[m/s]	Average max Vc [km/h]	Average range	Average engines power - max continous [HP]
Large	**9799**	**10.13**	**287**	**693**	**4211**
attack	7428	11.88	294	607	3260
multipurpose	6512	9.72	285	708	2640
transport	19876	8.40	283	777	8807
Small	**2163**	**8.89**	**253**	**601**	**700**
observation	1734	9.35	253	519	476
training	1728	9.40	248	671	515
utility	2593	8.51	255	655	914
Average	**7104**	**9.66**	**275**	**661**	**2971**

Relative parameters

The relative parameters are a good evaluation of the desired constructions. They are also proposed as inputs in the conceptual design phase.

Relative useful load

The relative useful load (M_p) is a ratio that defines the capability of helicopter lift. The relative useful load includes the fuel and the cargo mass. In helicopter missions, the operator is planning the quantity of fuel in the tanks. The rest of a free mass is allocated for the mission purpose. However, to carry more cargo at a shorter range, there are tasks where the tanks are not maximally filled. The ratio is given by the equation:

$$M_p = 1 - \frac{OEW}{MTOW} \qquad (1)$$

with: OEW – operating empty weight [kg];
MTOW – maximum take-off weight [kg].

A helicopter designer at the very beginning phase should assume the MTOW. To properly respond to the operator’s needs, it is necessary to plan the mass proportions and calculate the payload. The statistics for a relative useful load are shown in Fig. 11. Analysing the ratio in reference to the modern helicopter constructions, some statistics’ features can be pointed out. In accordance with the intended use, the transport helicopter has the best lift capability. For the attack helicopters, where the lift is designed only for the armament and the fuel, the relative useful load is at the lower level. The shown statistic can be a base to assess the concept design of the rotorcraft.

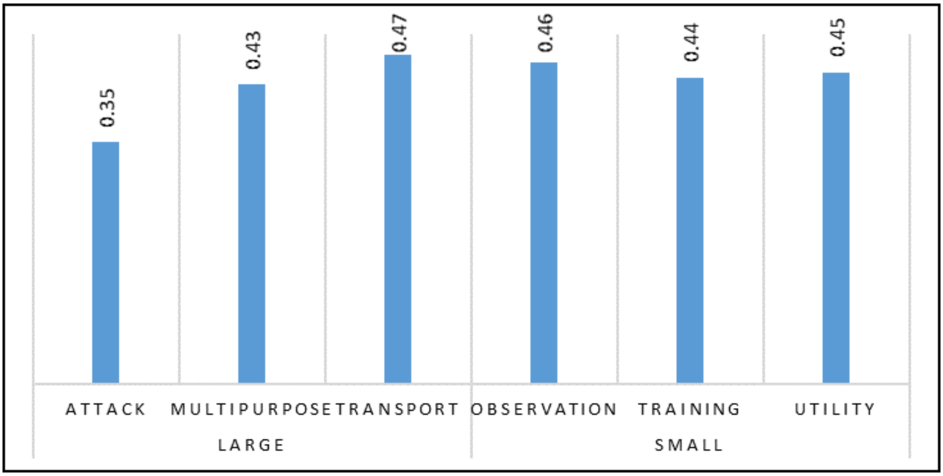

Fig. 11. Relative payload chart

In Figure 12, the trends for small and large helicopters are compared. What can be recognised is the fact that the trend for smaller MTOW is at the higher level. As a consequence, the conclusion can be drawn that the constructions with the smaller MTOWs are better than those for the larger machines. The main cause is the lack of geometry boundaries of the main rotor. This is another argument for the theory which says that achieving the optimal rotor parameters improves the construction performance.

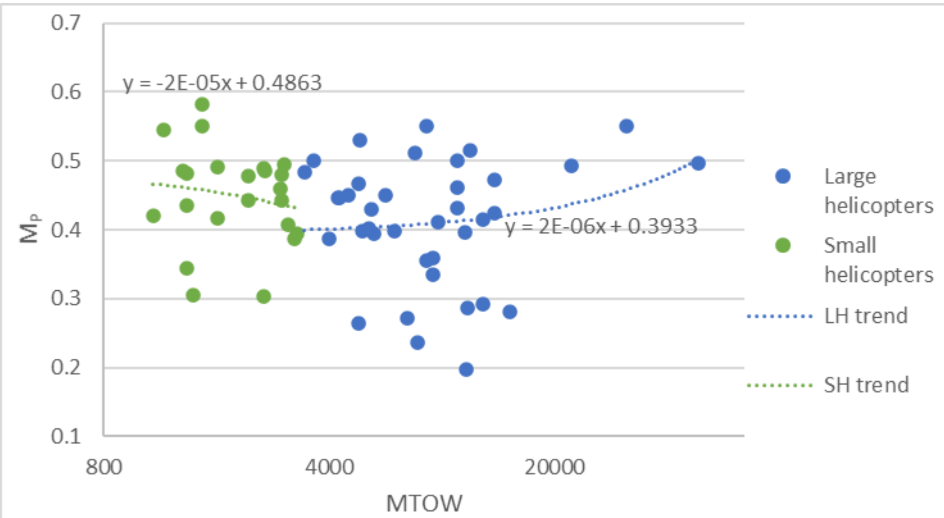

Fig. 12. Relative useful load trends

Disc load and power load

Other relative parameters, that help the designer to check the construction performance, are the disc load and the power load. These ratios, when calculated for the preliminary construction, should be compared to the static values.

The disc load is given by:

$$p = \frac{MTOW}{\pi R^2} \tag{2}$$

where R [m] is the main rotor radius,
and the power load is:

$$q = \frac{MTOW}{N_{PU}} \tag{3}$$

where N_{PU} is the power of the engines.

Clearly, if the ratios are larger, then the construction is more capable to lift the planned mass. The capability comes from the rotor geometry or the engines' power.

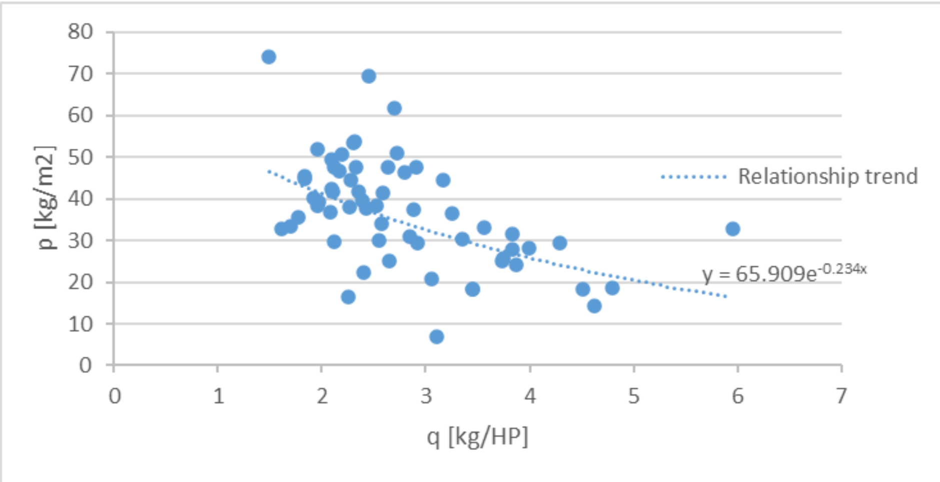

Fig. 13. Relationship between q and p parameters

The statistic relationship between two parameters is shown in Fig. 13. In the chart, the correlation trend is marked. If the disc load is at the higher value, then the power load is lower. The opposite situation takes place if the disc load ratio is bounded by geometry. That is recognised for the large helicopter, where the main rotor radius is longer and there is a risk of critical Mach number occurrence. For smaller constructions, the radius is smaller, and as a result it can be customised to the rotorcraft and it can produce relatively more lift force.

That gives an opportunity to estimate the engines (in a conceptual design phase) with the higher rotor thrust as a calculation input and as a result to obtain lower engine requirements. The statistic average values are presented in Table 4. These figures are good to compare the designed rotorcraft to modern helicopters.

Table 4. Statistic relative parameters

Helicopters	Average M_p	Average *p* [kg/m2]	Average *q* [kg/HP]
Large	**0.41**	**42.85**	**2.37**
attack	0.35	42.91	2.27
multipurpose	0.43	39.59	2.37
transport	0.47	49.61	2.46
small	**0.45**	**26.72**	**3.46**
observation	0.46	23.77	3.73
training	0.44	22.58	3.76
utility	0.45	29.97	3.16
All	**0.43**	**37.07**	**2.77**

The two parameters, described above, are another argument for the main rotor optimisation. When the main rotor capability to produce more lift comes from its own parameters, then it is more possible to optimise the powerplant selection with the reduced power requirements.

Rotor solidity

The rotor solidity ratio describes the rotor disc filling with the blades area. In the conceptual design, this parameter, with the statistical database, is fundamental for choosing the number of blades and the blade chord. The rotor solidity is described by:

$$\sigma = \frac{zc}{\pi R} \tag{4}$$

where *z* is the number of blades,

c [m] is the blade chord and

R [m] is the main rotor radius.

In Figure 14 the relationship between the parameter σ and MTOW is demonstrated. For small constructions, where the rotor velocity is greater, the lift surface can be diminished. However, if the radius and the speed are restrained, the lift is required to be generated by adding more area with the new blade or by extending the chord. Increasing the solidity, the rotor vibrations and mass are simultaneously risen. As a result, the blade loads are expanding. To reduce the rotor solidity, the lift force should be gained by improving the rotor performance with better airfoil or higher speed.

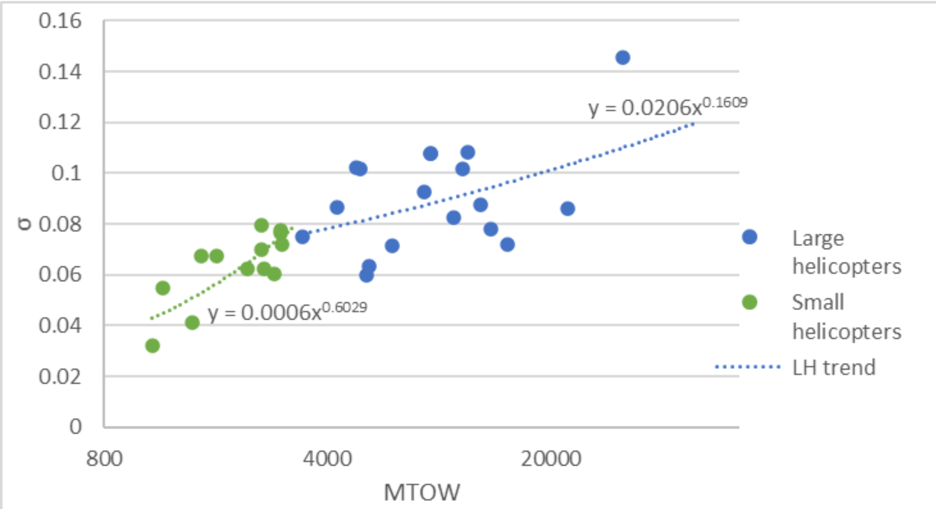

Fig. 14. Rotor solidity

Advance ratio

The advance ratio is a designed input parameter that describes the potential of helicopters' maximum cruising speed in accordance with the rotor's tip speed. It can be compared with statistic data to evaluate the proposed construction. It is described with the equation:

$$\mu = \frac{V_c}{U} \tag{5}$$

with: V_c – maximum cruise speed [m/s];
U – rotor tip speed [m/s].

However, to obtain full information about the rotor's potential, the calculated advance ratio can be also being compared with the maximum advance ratio, which is calculated for the local sound speed:

$$\mu_{max} = \frac{60-a}{\pi n D} - 1 \tag{6}$$

with: a – local sound speed [m/s];
n – number of blades;
D – main rotor diameter [m].

In Figure 15, both parameters are shown. It demonstrates that the rotors with the smaller MTOW, and as the result smaller geometry, have a capacity to increase the performance without the hazard of closing to critical Mach number. On the other side, the ratio can be a proof of the fact that modern rotor blades can be optimised, to increase the cruising speed, with the retraction of the critical Mach number at the higher speed.

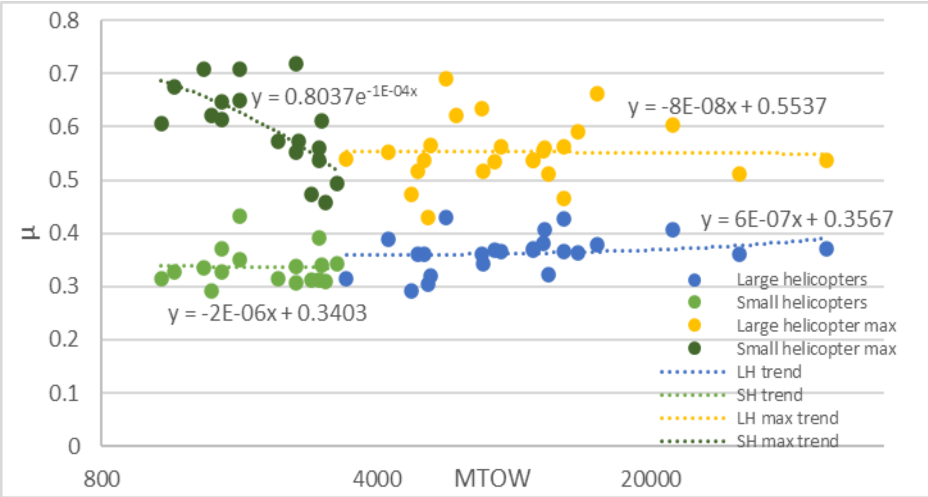

Fig. 15. Advance ratio comparison

Aspect Ratio

The aspect ratio is defining the proportion of blade chord to blade radius.

$$\lambda = \frac{c}{R} \tag{7}$$

Basing on the statistics data, shown in Fig. 16, a trend cannot be defined, however, the parameter can be bounded by the 0.04 to 0.08 value. The average value for all kinds of helicopters equals 0.06.

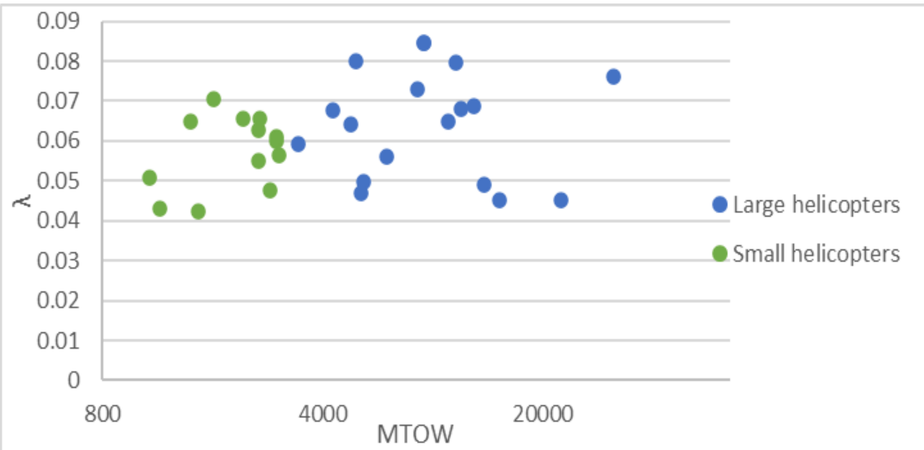

Fig. 16. Aspect ratio

Lock number

The lock number is a crucial ratio that defines the relationship between aerodynamic parameters and inertia forces acting on the blade.

The parameter is calculated with the equation:

$$\gamma = \frac{\rho a_0 c R^4}{I_\beta} \tag{8}$$

with: ρ – air density [kg/m^3];
a_0 – main rotor blade's lift curve slope [1/rad];
I_β – flap moment of inertia [kgm^2].

For military helicopters the Lock Number reaches values from 5 to almost 12. As it is shown in Fig. 17, when the MTOW increases, the ratio is also getting the higher rate. Rotor blades, with the higher Lock Number value, are less resistant to flapping, because of a limited moment of inertia placed in a denominator, with the greater geometric dimensions.

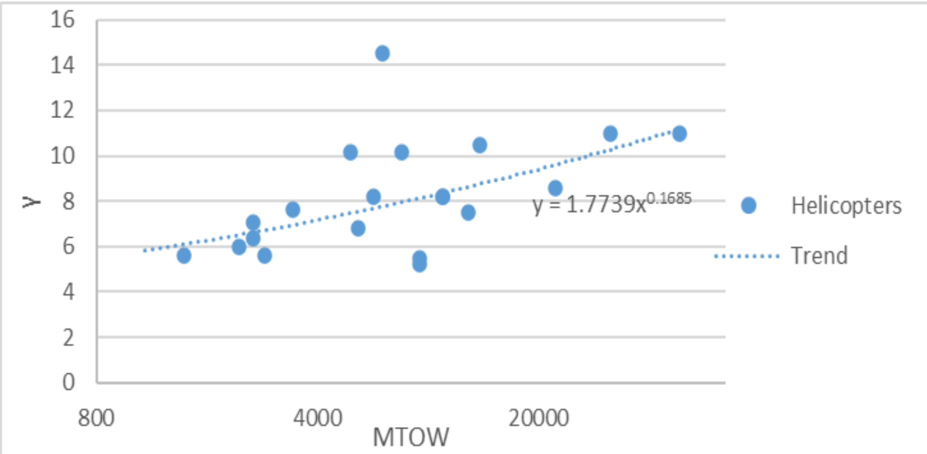

Fig. 17. Lock number

4. DESIGN INPUTS IN PRELIMINARY DESIGN

In order to show the implementation of design inputs in the preliminary phase of the design process, the main rotor initial calculations are presented. The main rotor estimation is the first step in a helicopter design.

4.1. Estimation of Maximum Take-off Weight

From operation prerequisites, there comes the MTOW. Taking into consideration the average values and descriptions, proposed in the previous chapters, some gross weight can be assumed. The Relative Useful Load ratio is applicable in this step to evaluate the required load capability in comparison with statistical data.

4.2. Calculation of a rotor radius

One of the first steps of the main rotor estimations is defining the rotor radius. The Disc Load factor, based on the gathered data, is a good design input to provide the radius length. Comparing the given operational demands with statistics, the first value of the rotor radius can be determined.

4.3. Calculation of tip velocity

The next point of a rotor design is a tip velocity estimation. This possibility provides an Advance Ratio. Taking into consideration the demanding maximum cruise speed, the tip velocity is able to be settled.

4.4. Calculation of a blade number and a chord value

Taking into consideration the Aspect Ratio from statistical data and Rotor Solidity, a blade number and a chord length can be obtained. Combining the mentioned Design Inputs into a function allows us to calculate the rotor parameters as expected.

4.5. Choosing an airfoil and inertial characteristic

The crucial phase of a preliminary main rotor design is choosing an airfoil. One of the proposed criteria of selecting the profile is the inertial characteristic of the blade. Taking into consideration the statistical Lock Number, and assuming the desirable flapping moment of inertia, the lift curve slope can be estimated. Its value helps the designer to choose the correct airfoil for the planned aircraft.

4.6. Iterative procedure

The proposed implementation of the Design Inputs should be applied to the iterative procedure as it is shown in Fig. 1 of the Design Wheel. The procedure can be implemented into numeric computing software or CAD environment to calculate the best helicopter parameters.

4.7. Design inputs calculated for a multipurpose helicopter

To show the Design Inputs in numbers, the calculations for the W-3 helicopter are proposed. The W-3 helicopter is a good example of rotorcrafts that were classically designed without using modern CAD/CAE/CFD software. Table 5 data are a basis for a further rotorcraft optimisation. Improving the ratios allows us to gain the better aircraft performance.

Table 5. Calculated design inputs

Parameter	**Equation**	**Numbers**	**Result**	**Average parameter for helicopters with similar MTOW (±1500 kg)**
Relative useful load	$M_p = 1 - \frac{OEW}{MTOW}$	$1 - \frac{3850}{6400}$	0.398	0.43
Disc load	$p = \frac{MTOW}{\pi R^2}$	$\frac{6400}{\pi \cdot 15.7^2}$	33.06	39.40
Power load	$q = \frac{MTOW}{N_{PU}}$	$\frac{6400}{2 \cdot 1100}$	2.9	2.23
Rotor solidity	$\sigma = \frac{zc}{\pi R}$	$\frac{4 \cdot 0.44}{\pi \cdot 15.7}$	0.071	0.07
Advance ratio	$\mu = \frac{V_c}{U}$	$\frac{72.2}{209.62}$	0.34	0.34
Maximum Advance Ratio	$\mu_{max} = \frac{60 - a}{\pi n D} - 1$	$\frac{60 - 340}{\pi \cdot 255 \cdot 15.7} - 1$	0.62	0.56
Aspect Ratio	$\lambda = \frac{c}{R}$	$\frac{0.44}{7.85}$	0.56	0.05
Lock number	$\gamma = \frac{\rho a_0 c R^4}{I_\beta}$	$\frac{1.21 \cdot 6.303 \cdot 0.44 \cdot 7.85^4}{1207}$	9.82	9.97

5. CONCLUSIONS

The analysis of constructions of modern military helicopters provides a diversified basis for a rotorcraft design. The airframes' distributions were based on EASA legislation, which allows a future designer to use the data in the projects that correspond, from the very beginning, with the applicable law.

In accordance with a mission purpose, characteristic features of helicopters constructions were shown in this work. The provided information is ready to be used in the conceptual design phase. Taking into consideration the operator's needs, a designer has a ready-to-use data that allows us to prepare a fist-look rotorcraft design, which is able to fulfil the modern warfare requirements.

The design inputs, presented in the third chapter, are accessible to evaluate the conceptual calculations and to assess their usefulness with comparison to other modern constructions. The ratios, given in the paper can also be used to calculate basic rotor dimensions and performance parameters.

The crucial conclusion of the work is that all of the rotor parameters determine helicopter's performance. Next phases of a conceptual design are based on the main rotor calculations. Power prediction and tail rotor parameters are limited by the obtained results. More efficient main rotor generates a better quality of input numbers for the next design stages, for example in the engines selection the main rotor thrust is the element of the equations. It could provoke lower power requirements, however, the powerplant selection is a separate optimisation problem which is not objective of this work and more conditions is needed to be considered.

It was also shown, that the existing helicopter can be an object of improvement for researches. The design inputs, presented in the work, can be indicators to evaluate the construction and to point the optimisation directions.

The need for rotor enhancement emerges in different helicopters lifecycle stages. This paper's considerations will serve as a basis for preparing the main rotors model with modern optimisation methods – using CAD, CAE, and CFD environments combined with mathematical multi-criteria optimisation calculations.

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Przegląd nowoczesnych konstrukcji śmigłowcowych wraz ze wskazaniem parametrów projektowych wiropłatów

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Streszczenie. Praca zawiera wyniki analizy współczesnych konstrukcji śmigłowcowych. Obejmuje porównanie prawie siedemdziesięciu konstrukcji wiropłatów podzielonych ze względu na rozmiar: zgodnie z wymaganiami EASA – duży i mały śmigłowiec. W ramach rozmiaru statki powietrzne zostały podzielone ze względu na cel misji. Proponowany podział dla dużych śmigłowców to: transportowe, wielozadaniowe i szturmowe, natomiast dla małych: obserwacyjne, szkoleniowe, użytkowe. Wyszczególniono najważniejsze cechy konstrukcyjne wiropłata. W pracy zaprezentowano średnie wartości wymiarów płatowców i wirników. Przedstawiono również układ wirników śmigłowca pod kątem przeznaczenia operacyjnego. Finalnie opisano parametry projektowe przydatne w projektowaniu wstępnym. Parametry opisano za pomocą wzorów matematycznych oraz dla każdego z nich zaprezentowano na wykresie zebrane dane statystyczne. W artykule pokazano zależność parametrów w funkcji maksymalnej masy startowej statków powietrznych. Wyznaczono trendy w celu dostarczenia narzędzi do oceny projektowanych śmigłowców. Dodatkowo przedstawiono możliwość wykorzystania parametrów jako zmiennych optymalizacyjnych.

Słowa kluczowe: lotnictwo, śmigłowiec, analiza, wirnik, wojsko