CODEN STJSAO ISSN 0562-1887
ZX470/1342 UDK 629.735.45.035.6

Helicopter Main Rotor Conceptual Design - Application to a Westland Lynx Helicopter

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Preliminary note

Helicopter design requires from the designers to make a lot of compromises and choices, sometimes affecting on positive parameters in order to improve global capabilities and performance. If these choices are made well, based on detail calculations and reliable input data, flight performances should be good and helicopter should be able to satisfactory sustain all the missions and tasks for which it is designed for. The following paper describes a shorter version of the initial design philosophy with an application to the Westland Lynx helicopter. This philosophy, of course with some specifics, could be applied in Croatia, in terms of determination of basics requirements and assumptions for making the right decision in selecting a specific type of an aircraft – both for the military and for civilian sector.

Konceptualna konstrukcija nosećeg rotora helikoptera - primjena na helikopter Westland Lynx

Prethodno priopćenje

Konstruiranje helikoptera zahtijeva niz kompromisa, ponekad na štetu nekih pogodnosti kako bi se mogle ostvariti druge mogućnosti koje su s time u izravnoj vezi. Ako se kompromisi na temelju proračuna i kvalitetnih ulaznih podataka pri konstruiranju nosećeg rotora pravilno izvedu, letne performanse bit će zadovoljavajuće, a helikopter će moći kvalitetno ostvarivati zadaće i misije za koje je namijenjen. U radu je na primjeru helikoptera Westland Lynx prikazan skraćeni proces definiranja i provedbe temeljnih faza konstruiranja te pretpostavki dobivenih temeljem početnog zahtjeva. Ovakva analogija, naravno uz svoje specifičnosti, može biti uspješno primjenjivana i u Republici Hrvatskoj u smislu determiniranja osnovnih zahtjeva i pretpostavki kako bi se uspješno donijela odluka o nabavci i odabiru određene vrste i tipa letjelice – kako za vojne, tako i za civilne potrebe.

Keywords
Flight performanse
Helicopter design
Main rotor

Ključne riječi
Konstrukcija helikoptera
Letne performanse
Noseći rotor

Received (primljeno): 2007-10-12
Accepted (prihvaćeno): 2008-04-10

1. Introduction

The main rotor is the most important concept of helicopter [1]. Proper design of the rotor is critical to meet the performance specifications for the helicopter as a whole. The preliminary design of the main rotor must include following key aerodynamic considerations [1]: *General sizing* (rotor diameter, disc loading, rotor tip speed), *Blade planform* (chord, solidity, number of blades, blade twist) and *Airfoil section(s)* which plays an important role in meeting overall performance requirements For that reason, designers take special care in selecting the main rotor parameters to insure the best possible hover performance, best forward flight performance, lowest costs, weight, noise, vibration, etc.

That is why the design of a helicopter main rotor is one of the most challenging aeronautical processes which require a lot of iteration during design phases. For instance, choice of aerofoil on rotor blade is very complex task which results with great increase of performance if it is done carefully.

In this study it will be shown, in shorter version, what are the main principles and ways of designing main rotor which is the crucial and most important element of every helicopter.

2. Rotor case study of Lynx helicopter

The helicopter represents the great number of systems with their own specifics and demands of which are many of them in collision. In order to design the main rotor, the designers first must be aware of the type of mission the helicopter is to be designed for. For example, if a good

Symbols/ Oznake

a	- sonic velocity, m/s - brzina zvuka	R	- rotor (blade) radius, m - najveći radijus kraka rotora
A	- rotor disc area, m^2 - površina diska rotora	T	- thrust, N - pogonska sila nosećeg rotora
A_b	- blade area, m^2 - površina lopatice	V	- air speed, m/s - brzina leta u odnosu na zrak
C_T	- rotor thrust coefficient - koeficijent pogonske sile rotora	V_{TIPmax}	- maximum tip speed, m/s - maksimalna brzina vrha lopatice
C_T/σ	- blade thrust coefficient - koeficijent pogonske sile lopatice	W	- gross weight, kg - ukupna masa
IGE	- Hovering In-Ground Effect - lebdenje pod utjecajem zračnog jastuka	w	- disc loading DL = T/A, kg/m^2 - opterećenje diska DL = T/A
ISA	- International Standard Atmosphere - Međunarodna standardna atmosfera	k	- induced power factor (1,15) - faktor inducirane snage (1,15)
M	- Mach number - Mach number	μ	- advance ratio - koeficijent napredovanja
M_{CRIT}	- critical Mach number - kritični Mach-ov broj	ρ	- density of air, kg/m^3 - gustoća zraka
OGE	- Hovering Out-of-Ground Effect - lebdenje bez utjecaja zračnog jastuka	σ	- rotor solidity, $N_c/\pi R$ - faktor ispune diska nosećeg rotora
P_i	- induced power, W - inducirana snaga	Ω	- rotational frequency of rotor, rad/s - kutna brzina rotora
r	- radial distance, m - polumjer diska nosećeg rotora		

hover performance is required, but forward speed is not too important, than an optimum blade twist for hover could be designed. This would lead to early retreating blade stall, so the forward flight performance would not be so good. On the other hand, if there is requirement for helicopter to have high forward speed (combat utility helicopters), than a rotor with only a small degree of blade twist but large amount of excess power will be considered as appropriate.

The initial rotor design starts with an aircraft performance requirement, which are given in document called Request for Proposal (RFP). For the Lynx helicopter this was set out as [2]:

REQUIREMENT: Helicopter of moderate size, range and payload capabilities; good manoeuvrability, high speed (min. 80 m/s*); good high altitude performance* (1,200 m ISA + 15 °C).

At the start of design process, the gross mass of an aircraft is not known, so it has to be estimated in order to start with calculations. From statistical data and by general assessment, the main requirement leads to an estimate of the aircraft gross mass of 4,100 kg. Also, the gross weight can be specified as one of most important parameter in RFP. A search of available power plants (at the time of Lynx design, the Rolls Royce Gem was the most suitable power plant), and the requirement for a twin engine concept (for security reasons) leads to an estimated installed power of 560 kW per engine.

When these two estimated data (gross weight and installed power per engine) are known the first step in rotor design process can begin.

3. Rotor blade tip speed

The rotor blade tip speed defines the retreating blade stall in forward flight, and advancing blade compressibility effect which all have influence on maximum forward speed. It also affects the helicopter noise and performance in autorotation. In design process there is a dilemma: should the tip speed be higher for low rotor and gear system weight and for a good air flow around retreating blade; or should it be low for low noise and for avoiding critical Mach number on advancing blade during high forward speed. The designer's goal is to choose the highest tip speed possible, with certain constrains, and one of these is the noise. It is generally agreed that tip speeds of more than 230 m/s are unacceptably noisy and that tip speeds of less than 150 m/s are quiet.

Of course, one of the major constrains is advancing blade Mach number, which is defined as [3]:

$$V_{\mathrm{TIPmax}} = a * M_{\mathrm{CRIT}} - V. \quad (1)$$

For an advanced airfoil, such as the RAE 9634 on tip section, the critical Mach number can be set as high as $M_{CRIT} = 0,87$.

The advance ratio for a helicopter, which represents a ratio between the horizontal component of an airspeed on rotor disk and angular velocity of blade tip ($\mu = V \cdot \cos\alpha / \Omega \cdot R$), is usually around 0,4 because dynamic stall and vibration become much larger at higher speeds.

Maximum hover tip Mach number is set so that the blades are not in transonic regime during normal helicopter operations. An estimate of the maximum allowable tip hover Mach number is found from the critical Mach number of the rotor lifting section during high angels of attack of a rotor blade. The front and rear of the rotor generates most of the lift in forward flight, but Mach number of the front and the rear does not change with forward speed, and is the same as the hover tip Mach number.

A typical angle of attack at $\mu = 0,3$ for the tip region is around 8° [2].

These requirements which show relations between forward flight speed and tip speed are plotted on a Figure 1. The design point, matching the performance requirement of high forward speed determinates rotor tip speed at $V_{TIP} = 210$ m/s which gives a cruising speed of 83 m/s [2].

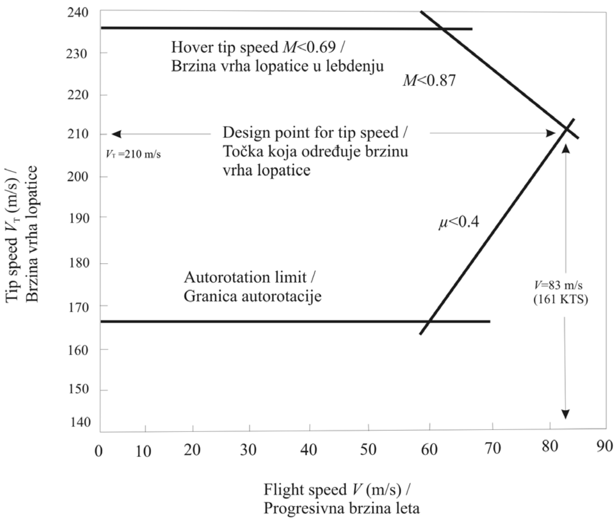

Figure 1. Forward flight speed vs. tip speed [1]

Slika 1. Odnos progresivne brzine leta s brzinom vrhova lopatica

4. Rotor blade area

A helicopter main rotor has an optimum angle of attack for its maximum figure of merit in hover, just like an airplane has an optimum angle of attack for its maximum lift-to-drag ratio. It is because the retreating blade operates at decreasing relative speed, while its maximum lift coefficient is limited by stall effect. The stalling characteristics of a rotor depend on the blades lift coefficient. For a helicopter, the thrust coefficient of the rotor is related to the mean lift coefficient of the blades as [1]:

$$C_T = \int_0^1 \frac{1}{2}\sigma \overline{C_L} r^2 dr = \frac{1}{6}\sigma \overline{C_L} \quad . \quad (2)$$

Therefore there will be a limit on the value of C_T/σ above which the stall occurs [4]:

$$\frac{C_T}{\sigma} = \frac{T}{\rho A (\Omega R)^2} \frac{A}{A_b} \quad . \quad (3)$$

so if we make first approximation that the thrust is equal to the mass, then the maximum blade area will be defined as:

$$A_b = \left(\frac{C_T}{\sigma}\right)^{-1} \frac{W}{\rho (\Omega R)^2} \quad , \quad (4)$$

where C_T/σ is maximum value which could be get before the blade stall. The C_T/σ parameter is very similar to the airplane lift coefficient.

The maximum C_T/σ before blade stall can be determinate by wind tunnel testing, flight testing, computer simulations or using a combined methods. A model of helicopter rotor can be tested in a tunnel and its thrust measured at different advance ratios.

However, if the thrust is plotted on graph of C_T/σ as non-dimensional value as a function of the advance ratio, then the model stall boundary will match well with stall boundary for the real rotor and can be used to estimate the required blade area for the new design. This is shown in Figure 2 (the Lynx rotor was originally designed for the RAE/NPL 9615 section [2]).

From Figures 2 and 3 it could be seen that the total blade area of rotor is 10 m^2 [2].

5. Rotor radius

In order to determinate the rotor radius it is necessary to know and study engine performance. The two Rolls Royce engines selected for the Lynx helicopter have a continuous power rating of 560 kW each. Take off power is slightly higher (115% of continuous power), and

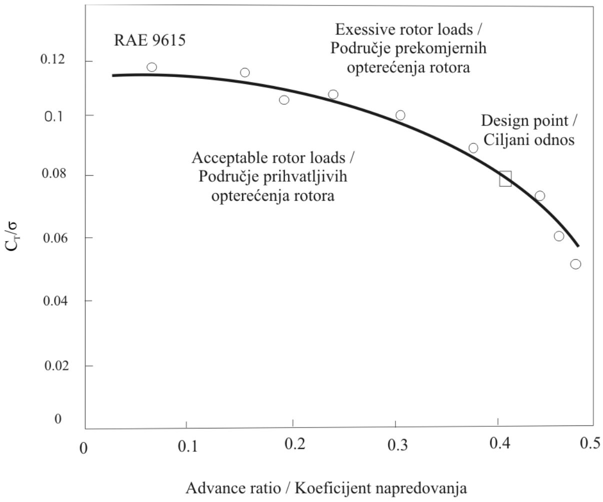

Figure 2. C_T/σ vs. advance ratio

Slika 2. Odnos C_T/σ (koeficijenta pogonske sile lopatice) sa koeficijentom napredovanja

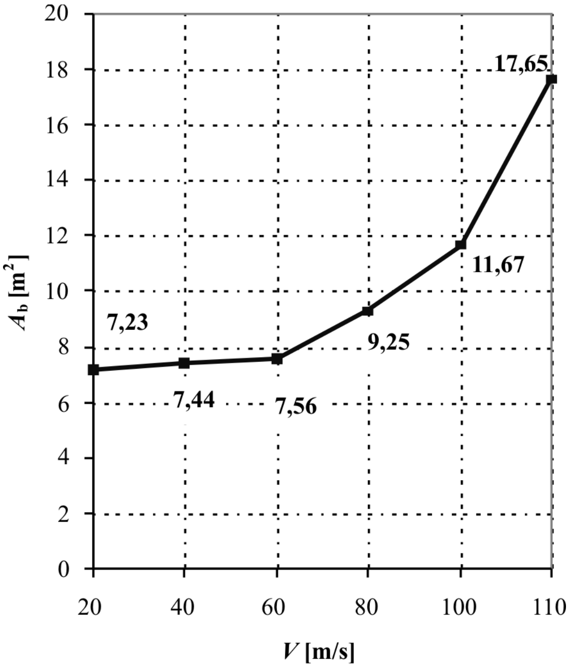

Figure 3. Determination of total blade area respecting forward speed

Slika 3. Određivanje ukupne površine lopatice u odnosu na progresivnu brzinu leta

contingency power is 130% of continuous power. The ideal induced power is [1],

$$P_i = \kappa T v_i, \tag{5}$$

where κ = 1,15 is an induced power correction factor or empirical correction to account for a multitude of aerodynamic phenomena, mainly those resulting from tip losses and nonuniform inflow [1]. This induced power (P_i) normalized with weight (specific power loading) is plotted in Figure 4 as a function of disc loading. In order to get better estimate of the required power, it is necessary to take into account of the profile power to overcome aerofoil drag, tail rotor power, transmission losses and downwash power (the rotor is sending downwash to the fuselage, thus increasing the required power). It is estimated that due to all these additional losses, the required power have to be increased by 66 % [2] and this line as P_2 is also plotted on the Figure 4. A third line (P_3) shows the effect of altitude on the power (multiply the power P_2 by $1/\sqrt{\rho/\rho_0}$). Finally, the engines will also be affected by altitude and temperature, and for 4,000 ft and ISA+15° the drop in the performance of the engines. To include that influence, line P_3 is increased by 35 % to get line P_4 [2]. On the Figure 4, the twin engine continuous power is added as a line and intersection between this line and P_4 is the design point for required disc loading. From graph 4 the result in a disc loading is 32 kg/m^2.

Following definition of disc loading rotor radius is:

$$R = \sqrt{\frac{W}{\pi w}} = \sqrt{\frac{4100}{32\pi}} \tag{6}$$

and for design blade, radius is 6,4 m.

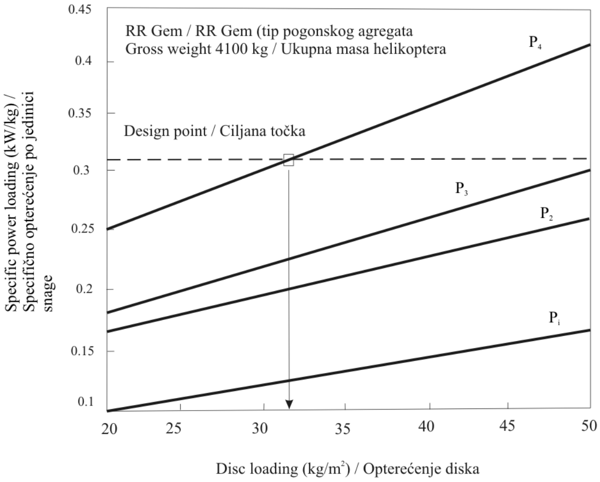

Figure 4. Finding disc loading from a specific power loading

Slika 4. Određivanje opterećenja diska iz specifičnog opterećenja po jedinici snage

6. Number of blades

The helicopter performances are significantly affected by choosing number of blades after total blade area has been selected and it is usually based on dynamic criteria. With the small the number of blades, the vibration level will be greater but designing the hub will be easier so the costs will be lower. The hub on Lynx helicopter is modern and relatively solid so rotor has enough power for controlling the helicopter, and to give the necessary manoeuvrability. Number of blades of the rotor represents a choice, because when the total blade area has been selected, dividing it into a certain number of blades isn't usually connected with performance but performance may be affected by that choice. Hence, the smaller the number of blades, the negative tip vortex from one blade in hover can be avoided by the following blade. Also the chord can be larger to lower the angle of attack in order to avoid stall. However, in that case, the span to chord ratio could reach 8, what means that tip stall will cancel all of the previous solution's benefits. In case of greater number of rotor blades, during forward flight tip vortex will be softer so the induced power will be lower than in the case with low-blades numbered rotor. However, it may result with low torsion stiffness of the blade to resist the aerodynamic pitching moments which occur in normal forward flight. This could lead to blade twisting which could negatively influence performance and flight safety.

All these advantages and disadvantages based on the number of the blades represents relatively small problem which is not crucial factor, but plays an important role in helicopter design. Most of designers prefer four blade rotor as the compromise between to few and to many (more than four blades results in technically complex hub design, extra drag and weight). In case of the Lynx helicopter the four blade rotor is chosen the four blade rotor which gives to the helicopter optimum degree of manoeuvrability with solid hub design. The aspect ratio for that rotor is 16,1 which results in good aerodynamical performances, and the general specifications are presented in Table 1.

Table 1. Lynx main rotor specifications [2]

Tablica 1. Specifikacije nosećeg rotora helikoptera Lynx

Blade number / Broj lopatica	4
Tip speed / Brzina vrha lopatice	210 m/s
Diameter / Promjer rotora	6,4 m
Chord / Tetiva	0,39 m
Advance ratio / Koeficijent napredovanja	16,1
0-65% span / raspon od 0-65%	RAE9648
65-85% span / raspon od 65-85%	RAE9645
> 85% span / raspon > 85%	RAE9634

Rotor hub with blades represents rigid helicopter rotor type, which means that there are special hinges which connects blades with the hub in order to allow them flapping and led-lag motion. The flexible oval section of titanium alloy allows for blade flapping and flexible titanium alloy cylindrical section allows for blade lead-lag motion.

As a result, the rotor should have good high speed performance. General performance data are given in Table 2.

Table 2. General performance data (for illustration purpose only) [2]

Tablica 2. Opći podatci o pefrormansama (samo kao primjer)

Maximum T/O mass / Maksimalna masa u polijetanju	5,330 kg
Maximum cruise speed / Maksimalna brzina krstarenja	255 km/h
Range / Dolet	540 km
Operative ceiling / Operativni vrhunac leta	3,600 m
Maximum hover OGE / Maksimalna visina lebdenja bez utjecaja zračnog jastuka	2,050 m or 340 m at ISA+15°
Maximum hover IGE / Maksimalna visina lebdenja s utjecajem zračnog jastuka	2,700 m or 1180 m at ISA+15°
Maximum climb / Maksimalna brzina uzdizanja	10,1 m/s

7. Conclusion

Helicopter design requires from the designers to make a lot of compromise and choices, sometimes affecting on positive parameters in order to improve global capabilities and performance. For example, improving the range of the helicopter requires lowering the gross weight and more fuel, which at the end increase the gross weight. Furthermore, at the beginning of the design, the designers have to make some assumptions in order to create basis for the calculations. Preliminary terms are gained from a mission types in which it is supposed to be used in. At first the gross weight is predicted and than the required power for hovering and forward flight. When it is not possible to reach the required standards by calculations, the basic assumptions has to be changed. If the choices during the design are made based on the detail calculations and a reliable input data, flight performances should be good and helicopter should be able to satisfactory sustain all the missions and tasks for which is designed for. These could be seen on the Lynx example, which is one of the most manoeuvrable multipurpose civil/military helicopters in the world.

REFERENCES

[1] LEISHMAN, J. G.: *Principles of Helicopter Aerodynamics*, Cambridge University Press, 2000.

[2] *Lynx Rotorcraft Flight Manual*, Agusta-Westland, 1995.

[3] CORTTREL, M.D.: *A study of the effect of design parameter variation on predicted tilt-rotor aircraft performance*, Naval Postgraduate School, NASA, 1988.

[4] JONHSON, W.: *Helicopter Theory*, Dover Publications Inc., NY, 1994.

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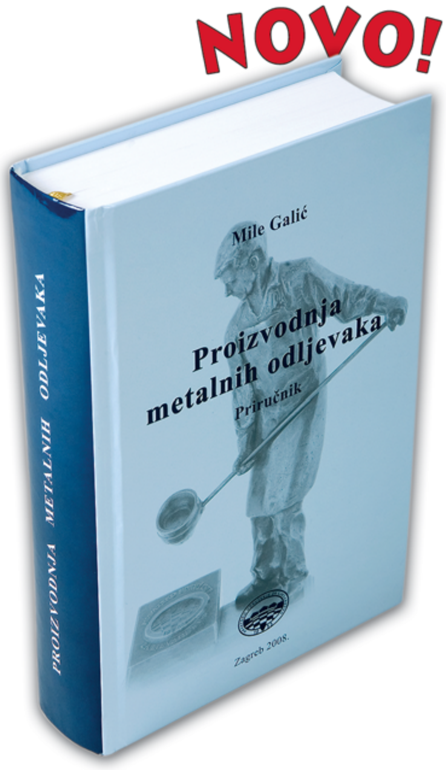

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