Design and feasibility study of a two-seat kitcopter

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Abstract
The paper discusses some major design reflections for a two-seat gas turbine equipped helicopter with a design AUM of 640 kg. The engine, the main and tail rotor, the helicopter performance and the drive train are tackled. For the main rotor, a blade-element-momentum-theory program allowed the determination of the optimum working domain for the helicopter main rotor in hover OGE. From this design study, some important helicopter performance characteristics have been derived. Weight is a major drive factor in the design of an aircraft and particularly on a helicopter with a small payload ratio. In a helicopter, the transmission drive system has a significant impact on the total weight of the helicopter. Therefore, an examination of the important drive train components results in the optimization of a subcritical and a supercritical drive train system.

1. Introduction

A Belgian industrial, the company Winner scs, supported by the Walloon Region of Belgium (DGTRE), has charged our service at the University of Brussels (ULB) to design a two-seat helicopter powered by one small kerosene-fuelled turboshaft based on their previous single seat helicopter powered by a piston engine. The helicopter is intended to be used for mainly training purposes but also for leisure flight. It would be certified in the CNSK category at the French DGAC. The final product must be a low cost option for potential helicopter customers.

During the early design stages, a low main rotor disk loading with a minimum main rotor blade number emerged as the most power efficient solution for the helicopter. The use of off-the-shelf *OTS* components reduces cost and this turns out as the major drive factor for outsourcing the development of critical parts such as the main rotor, for which several options exist. A gas turbine engine offers not only technical advantages, such as a weight and vibration reduction, but it is also economically attractive by launching a new market segment : a gas turbine equipped kitcopter. The weight reduction and optimisation has a significant impact on the helicopter performance. The drive train claims a large share of the total weight. Therefore, a study of the drive train weight allows the determination of the mass-critical components and hence the possibility of reducing these masses by modifying, replacing or moving these components in the drive train. The all-up-mass *AUM* of the helicopter has been estimated to be around 640 kg, which is well below the maximum mass imposed by the BCAR-VLH regulations, adopted by the DGAC for the CNSK category (Certificat de Navigabilité Spécial d'aéronef en Kit). Figure 1 shows a 3D-impression of the new two-bladed helicopter.

Figure 1 : A 3D-view of the Winner B150 kitcopter

2. WPS-150 Hybrid turboshaft engine

The heart of the helicopter consists of a 150 BHP* strong, 39 kg heavy, WPS hybrid turboshaft engine. The engine is based on the Solar T-62T-32 turboshaft engine, a frequently used auxiliary power unit on large helicopters such as the Boeing CH-47 Chinook. The hybrid engine differs from the original engine having other bearings, revised compressor and turbine wheels and incorporating several weight-reducing part replacements, cutting the original engine weight by a factor of about two. Hence, the engine does not comply with e.g. EASA CS-APU regulations, though, the CNSK certification allows for less stringent requirements, offering the possibility of the use of a hybrid turboshaft after performing a mutual agreed engine test campaign.
Figure 2 shows a cutaway of the engine, while Table 1 summarises some important engine characteristics.

Table 1: WPS-150 Hybrid turboshaft characteristics [a]

Maximum continuous power, ISA SLS (BHP)	150
Maximum Exhaust Gas Temperature (°C)	638
Compression ratio	+/- 4
Air mass flow (kg/s)	0.9 - 1.2
Fuel mass flow (g/s)	10 - 18
Working Envelope	Sea Level / -54 - 51.7°C 8000 ft / -54 - 32.2°C

[a] All values apply for ISA SLS pressure, unless stated otherwise.

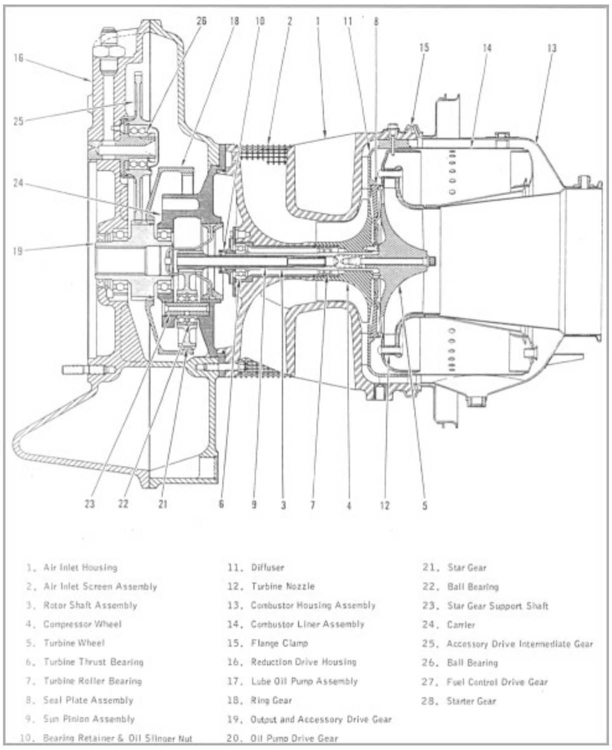


Figure 2 : Solar turboshaft engine cutaway

* Maximum continuous power, International Standard Atmosphere (ISA), Sea Level Static (SLS)

3. Main rotor design

3.1 Main rotor architecture and characteristics

The main rotor blades and head are critical helicopter components. The design and construction of these parts require a profound knowledge in this specific domain, especially when one considers a modern and weight saving architecture, incorporating composite and elastomeric materials. In view of these considerations and because of cost efficiency, the design and development should be outsourced to a specialized company, offering a tailor made reliable and kit friendly solution. Such a company was found and a collaboration agreement was established.

The company offers two airfoil profiles for the OTS rotor blades. After conferring with the company, the NACA 23012 profile was selected. The main rotor blades will be constructed of a carbon fibre material outer skin, wherein a rigidifying body such as foam or honeycomb will be applied. A correct amount of lead is inserted in the blade to obtain good dynamical characteristics and autorotational capability. The blade maximum obtainable length is limited to 3.82 m. The maximum blade radius $R_{T,m}$ figures 4.1 m. The blade will not incorporate taper and hence the chord length c along the blade should figure 0.195 m. The blade mould allows for a maximum blade twist angle $\theta_{tw,m}$ of -8° (washout). Larger blade twist angles introduce blade structural instabilities. The use of exotic materials overcomes this twist angle boundary, but it would turn the helicopter unaffordable in the considered “low cost” niche.

The main rotor head connects the rotating drive shaft with the blades, allowing the blades to produce lift. Simultaneously, it must allow the blades to flap, to swing (lead/lag) and to feather, while withstanding rapidly changing aerodynamic loads and large inertial forces, such as the centrifugal force.
For a low mass helicopter, a two bladed teetering rotor (Figure 3) can be selected. This configuration incorporates a lightweight, reasonably simple and reliable rotor head. Therefore, a two bladed teetering rotor suits best the requirements of a kit-helicopter.

Figure 3 : Robinson R22 articulated teetering rotor

Although the company offers an articulated teetering rotor, a less complex rigid teetering rotor avoids the necessity of an intensive rotor alignment flight campaign, though at the expense of more rotor induced vibrations. For a kitcopter, system complexity might compromise its reliability due to a possible lack of the homebuilder skills. Consequently, the rigid teetering rotor should preferably be installed on the helicopter.

The main rotor head can be equipped with conventional bearings or with elastomeric bearings. The elastomeric bearing allows the blade to feather by material deformation. This bearing consists of bronze lamellae bonded on rubber layers. It has the advantage of not requiring any form of maintenance, its ease of installation with no possibility of wrong installation and reduced price when purchased in large quantities. The bearing life is fixed. The disadvantage is that it can only be used in rotors where the centrifugal forces are limited to 9 tons. Not complying with this requirement obliges the use of conventional bearings, which require much more maintenance and of which the installation invokes additional difficulties. Hence, the main rotor centrifugal forces merit investigation, not only for blade strength and flapping angle, but also for the sake of rotor head complexity and reliability, which strongly depend on the bearing type. It needs no further explanation that one should strive for elastomeric bearings.

3.2 Main rotor working domain

Two independent variables have a large influence on the total helicopter system : the rotor tip radius R_T and the rotor pulsation N_{MR}. R_T and the product $R_T N_{MR}$ principally determine the main rotor power requirement P_{MR}. N_{MR} has a large influence on the drive train system components, their volume and weight.
Other important variables are blade twist angle θ_{tw}, blade tip Mach number M_{TIP}, helicopter weight, rotor maximum-load-factor n_{LF}, which should not be lower than 2, and the minimum operational atmospheric conditions for the helicopter. Winner scs premised the latter conditions (Table 2).

Table 2: Minimum kitcopter operational conditions

	AUM (kg)	Altitude (ft)	Temperature (°C)
ISA SLS Conditions	700	SL	ISA SLS
Hot and High	640	5000	ISA+20

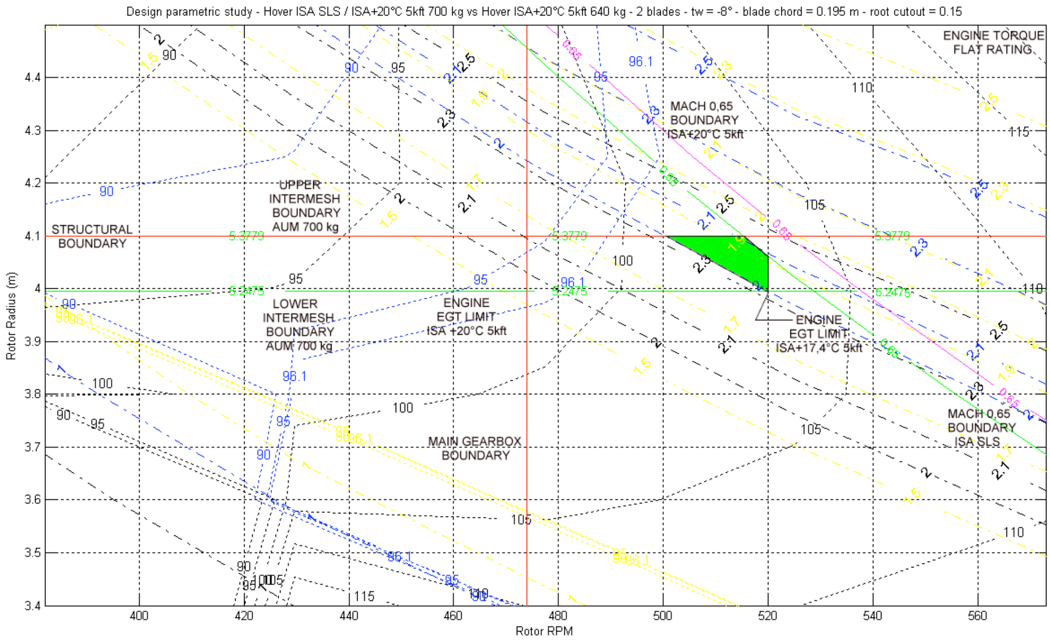
Flying at the conditions stated in Table 2 influence the required main rotor power P_{MR} as well as the available engine power P_A when encountering the engine limits (torque or EGT, Table 1). The tail rotor, aerodynamic interference and mechanical drive train losses absorb about 20%[2] of the maximum available engine power. These effects are incorporated in the engine curves represented on Figure 4.
A root cut-out factor x_0 of 15% has been adopted for the main rotor performance calculations. This value represents the amount of the blade radius starting from the hub, that does not produce any lift but contributes to the rotor drag.
Prouty[1] derives that a θ_{tw} of approximately -14° reduces maximally the main rotor power requirement in hover. Though, the OTS solution limits θ_{tw} to -8°. This seems more than sufficient since the rotor will not continuously work in hover conditions and moreover, the selected washout incorporates already about 80% of the obtainable reduction in rotor power consumption due to twisting. Figure 4 shows the results of the parametric main rotor study in hover. Table 3 tabulates the various limits defining the *green-coloured* main rotor working domain.

Table 3: Main rotor working domain variables limitations

$R_{T,m}$ (m)	4.1
$M_{TIP,m}$ (noise and drag divergence[3]) (-)	0.65
n_{LF} (for operational conditions, Table 2) (-)	2
Ultimate single stage gearbox reduction ratio (-)	6
Engine limits	Table 1
$N_{MR,m}$ (main rotor power and transmission losses confinement) (RPM)	520

Some explanations are due here. The figure states clearly that for the operational conditions and the suggested main rotor working domain (Table 4), AUM influences the main rotor power requirement P_{MR} tremendously, even though flying at a higher altitude and temperature. The iso-power-lines are nose shaped, suggesting the existence of an optimum power line. Likely, the optima coincide with a certain average rotor lift coefficient.
n_{LF} must be equal to or higher than 2 in order to guarantee helicopter manoeuvrability with a sufficiently large rotor stall safety margin. The higher the temperature and the lower the pressure, the larger the required blade pitch angle and consequently the closer the rotor is operated near stall. Hence, for the AUM of 640 kg at 5000 ft, ISA+20°C, n_{LF} becomes a limiting factor.
M_{TIP} cannot exceed 0.65 ($M_{TIP,m}$) for noise and power issues. The colder the atmosphere, the higher M_{TIP} becomes for a given rotor tip speed, depending on the product $R_T N_{MR}$. Therefore it follows that M_{TIP} limits the working domain when operating the rotor at ISA conditions (neglecting cold days).

Besides n_{LF} and M_{TIP}, a structural blade limit imposed by the blade manufacturer, confines R_T to 4.1 m ($R_{T,m}$). P_{MR} and transmissions losses set bound to the maximum main rotor speed $N_{MR,m}$: 520 RPM.
Note that although the rotor satisfies the operational conditions, the P_A does not fulfil the expectations. Indeed, while delivering the required power P_{MR}, the engine runs up against the EGT limit when flying at ISA+17.4°C, 5000 ft atmospheric conditions. This is 2.6°C below the initially determined value (Table 2), though, this deficit remains quite acceptable.



Legend		
Black : 700 kg ISA SLS	Blue : 640 kg ISA+20°C 5kft	Yellow : 700 kg ISA+20°C 5kft
Dotted lines :	main rotor power required P_{MR} (BHP)	
Dash-dot lines :	main rotor maximum-load-factor n_{LF} (maximum lift to weight)	
Green zone :	main rotor parameter domain of interest	

Figure 4 : Main rotor working domain

Table 4: Main rotor working domain, tabulated [b]

N_{MR} (RPM) → / R_T (m) ↓	**500.5**	**507.5**	**515.0**	**520**
4.10	B	<>	B	-
4.06	-	B	<>	B
4.02	-	-	B	B
3.99	-	-	-	B

[b] The tabulated values are derived from Figure 4.

The intermeshing boundaries can then be derived. They are explained in paragraph 4.2.

4. Tail rotor design

4.1 Tail rotor diameter and rotational speed

A good estimate for the tail rotor diameter D_{TR} results from the correlation[4] :

$$D_{TR} = \frac{2R_T}{7.15 - 0.0553 DL_{MR}} \qquad \textbf{(1)}$$

where DL_{MR} represents the main rotor disk loading (kg/m^2). DL_{MR} depends on AUM and R_T. Let us now choose the maximum AUM for determining D_{TR}. (1) shows that by so doing, D_{TR} remains on the safe side adopting a larger value. Applying (1) to Table 4, preliminary design values for D_{TR} appear (Table 5).

Table 5: Tail rotor diameter D_{TR} for main rotor working domain [c]

R_T (m)	**D_{TR} (m)**
4.10	1.2779
4.06	1.2683
4.02	1.2587
3.99	1.2516

[c] Values calculated for AUM = 700 kg.

Prouty[1] made a survey of several helicopters. For helicopters using a symmetrical airfoil such as NACA 0012 for the tail rotor, the tail rotor tip speed amounts to around 200 m/s. Using the D_{TR} values corresponding to the R_T boundaries of the main rotor working domain, N_{TR} ranges now in between 2900 and 3100 RPM (rounded off).

4.2 Tail boom length

From a survey of competing and existing helicopters, one observes that the tail boom length is chosen just long enough such that the main rotor and tail rotor do not intermesh. For the design of the kitcopter, the sum of R_T and D_{TR} (intermesh boundaries) should be equal or less than the vertical distance between the main rotor shaft and the outermost horizontal tail rotor tip position. Figure 4 shows the intermesh boundaries for the limiting R_T values. Hence, the tail boom length L_{TR} should now range in between 4.62 and 4.74 m. Remark that L_{TR} may be longer or smaller, but for the latter case, both rotors cannot collide during any flight condition. For the weight optimisation process, the values for L_{TR} are uncoupled from the intermeshing boundaries, allowing for a parametrical examination of L_{TR} on the drive train weight.

5. Performance analysis

Before broaching the performance analysis, the authors would like to emphasise that the calculations leading to the results shown in the subsequent sections do not consider any engine or rotor stall limiting factors.

5.1 Absolute ceiling

Figure 5 shows the absolute ceiling characteristics of the helicopter for hover in ground effect *IGE* and out of ground effect *OGE*. For respectively OGE and IGE, the absolute ceiling amounts to approximately 5250 ft and 9000 ft. Logically, the iso-ceiling lines tend to follow the iso-power-lines (P_{MR}) closely.

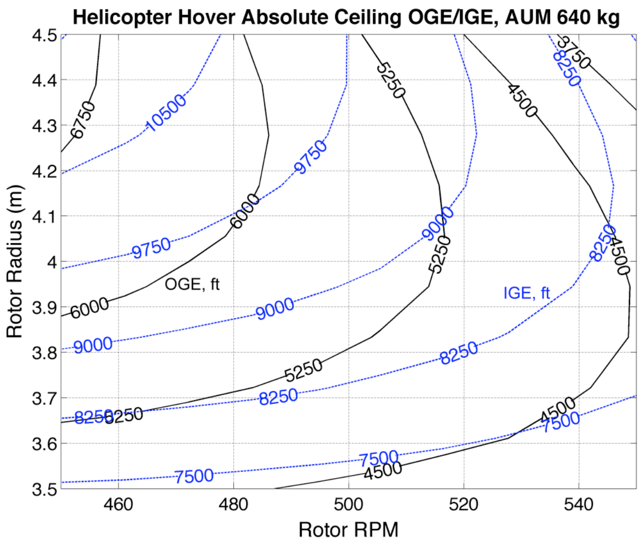


Figure 5 : Helicopter OGE/IGE hover absolute ceiling

5.2 Maximum horizontal speed

The results discussed in Figure 6 enclose the maximum horizontal speed $v_{h,m}$ of the helicopter in ISA SLS atmospheric conditions. For the considered main rotor domain, $v_{h,m}$ approaches 90 kts. Helicopter excess power *EP* calculations determined $v_{h,m}$. On the graph, the main rotor advance ratio μ is also plotted. The μ values remain well within the 0.2 to 0.25 interval, which concurs with μ of existing helicopters[1].

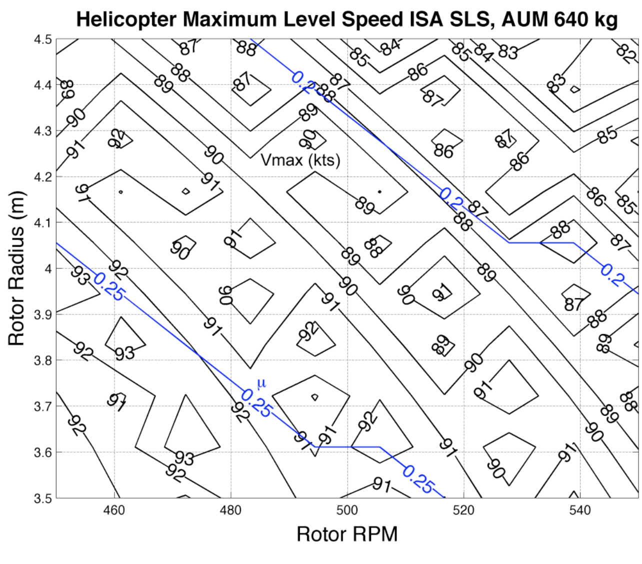


Figure 6 : Helicopter maximum horizontal speed

5.3 Maximum rate of climb

The maximum rate of climb ROC_m can be estimated by[2] :

$$ROC_m = \frac{EP_m}{9.80665 \times AUM} \qquad \textbf{(2)}$$

At the maximum excess power EP_m, a corresponding forward speed, here represented by μ_{bucket} can be found – also called "bucket speed" –. Consequently, if we can calculate this speed, EP_m can be determined for each rotor configuration, thus allowing an estimation of ROC_m. Johnson[2] suggests for μ_{bucket} :

$$\mu_{bucket} = \left(\frac{\kappa \cdot {C_T}^2}{3 \frac{f_e}{A_R}} \right)^{\frac{1}{4}} \quad \textbf{(3)}$$

with,

$$C_T = \frac{9.80665 \times AUM}{\rho A_R \left(\frac{\pi N_{MR}}{30} R_T \right)^2} \quad \textbf{(4)}$$

$$A_R = \pi R_T^2 \quad \textbf{(5)}$$

$$\kappa = 1.2 \quad \textbf{(6)}$$

$$fe = 0.929 \text{ m}^2 \quad \textbf{(7)}$$

Figure 7 shows the results obtained for ROC_m. The ROC_m approximates 1500 ft/min for the observed main rotor operating domain. The calculated ROC_m corresponds with the instantaneous climb speed when departing from level flight. As soon as a vertical climb speed exists, the ROC will decrease due to an increased helicopter surface exposure to the airflow, introducing a drag rise.

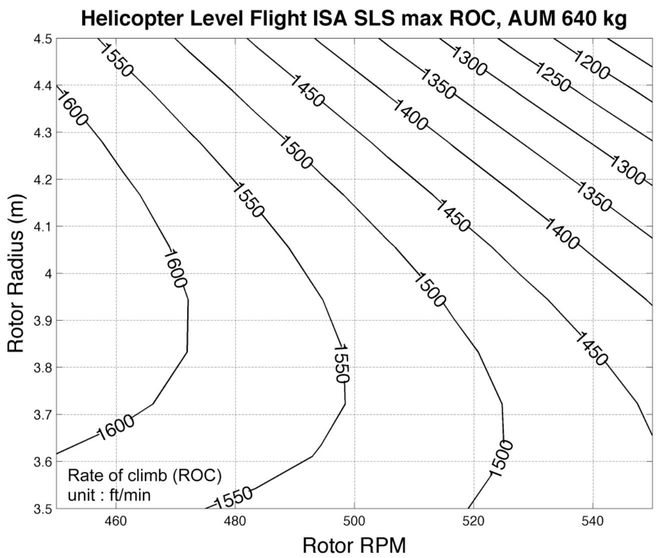


Figure 7 : Helicopter maximum rate of climb

6. Drive train weight considerations

The drive train transmits the engine power towards the main and tail rotor and makes them work at the required rotational speed. There exist multiple ways of doing this job, though, only a few will support a weight friendly solution. Figure 8 explains the contemplated drive train architecture for the kitcopter.

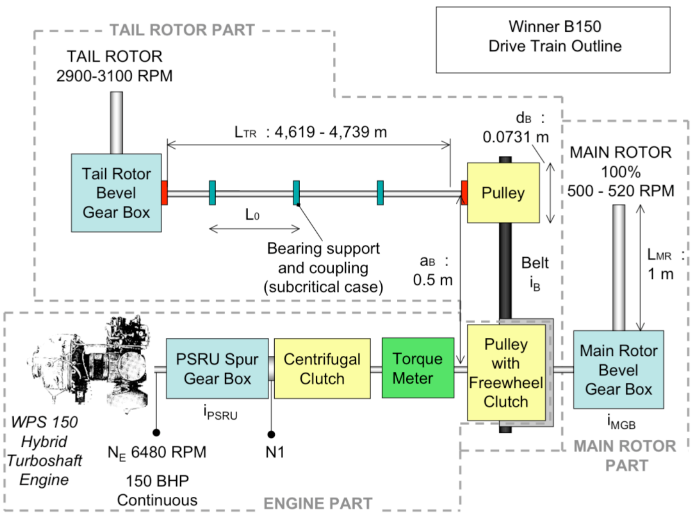


Figure 8 : Sketch of the suggested drive train architecture

A thorough weight optimisation study made by Buysschaert and Vanbellinghen[5] showed the necessity to split up the drive train into three parts : an engine part a main rotor part and a tail rotor part. The optimisation process then looks for an optimum combination of the gearbox, timing belt system and shaft variables. An important issue emerges from the tail boom shaft, which connects the large pulley of the timing belt system with the tail rotor gearbox. The shaft can be operated subcritically or supercritically, where the shaft turns respectively at a speed below the first critical bending frequency or above. A supercritical shaft has the advantage of weight, though, introduces complexity into the drive train, which should be avoided when no detailed research can be performed on this field. Moreover, there are currently not many helicopters equipped with a supercritical tail boom shaft. Hence, experience might be chosen above weight reduction. This paper reflects the weight survey of both systems in Figures 9 and 10.

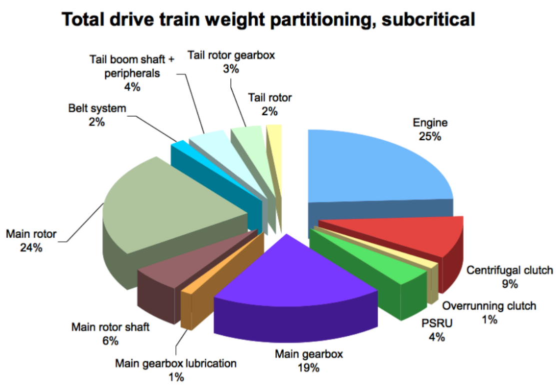


Figure 9 : Subcritical drive train system weight survey. Total mass : 161 kg

The weight consuming parts consist of the engine, the main gearbox and the main rotor. Though the tail rotor part only represents a mere 9% and 11% for respectively the supercritical and the subcritical system, the influence it has on the position of the centre of gravity cannot be neglected. The impact it has on the helicopter handling qualities is subject of further research.

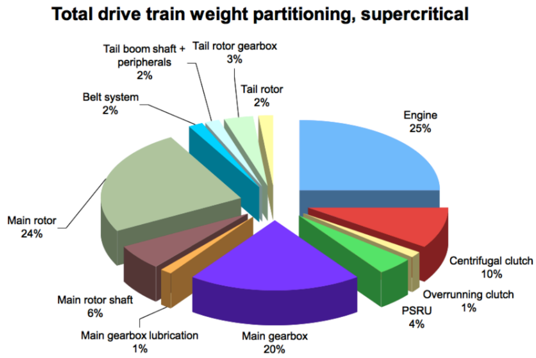


Figure 10 : Supercritical drive train system weight survey. Total mass : 157 kg

Comparing the mass of both systems, a supercritical solution reduces the mass of the drive train with approximately 4 kg. It takes up only 2% of the drive train system weight and about 0.1% of the helicopter AUM.

7. Conclusions

The ongoing study on the development of a two-seat turboshaft equipped kitcopter for the company Winner scs is very promising. A turboshaft gas turbine engine has been found for the helicopter and it fulfils the power requirements established by a BEMT calculation program of which the input parameters are defined by the operational conditions. Several boundary conditions exist, effectively constraining and consequently defining the main rotor working domain. From these values, an estimation of the tail rotor dimension and tail boom length emerged. The preliminary performance analysis shows acceptable results, though, might be a little too optimistic. The weight of the helicopter has been shown to be an essential factor for the power requirements. Hence, one should strive for a maximum weight reduction. Since the drive train represents a major share of the helicopter total weight, a study looked for optimising the drive train system for minimum weight. The paper reflects some important results of that ongoing work.

Acknowledgements

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