Design and Feasibility Study of a Turboshaft equipped Two-Seat Kitcopter

Frank Buysschaert , Patrick Hendrick

Université Libre de Bruxelles
50 F.D. Roosevelt Avenue, Brussels, 1050, Belgium
e-mail: frank.buysschaert@ulb.ac.be

Key words: Kitcopter, Turboshaft, Design, Feasibility.

Abstract: The paper discusses some major design reflections for a two-seat gas turbine equipped helicopter with a main rotor designed for an AUM of 650 kg. The helicopter gross weight estimations, 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 verification of a safe 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 are discussed in this paper.

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

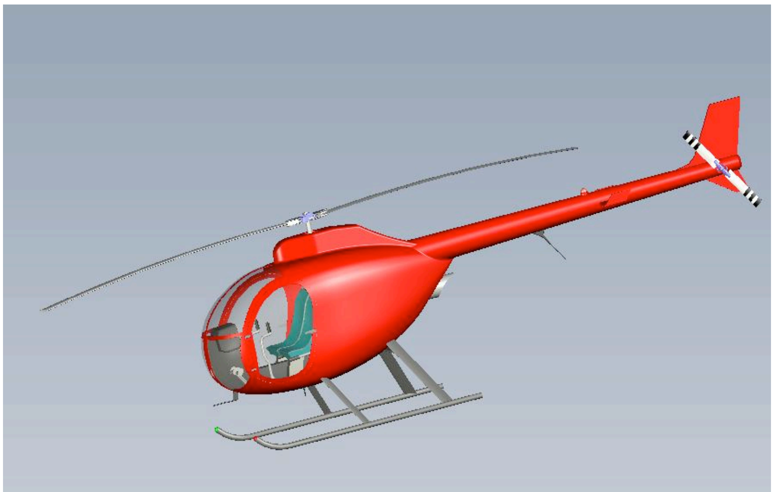

Figure 1 : A 3D-view of the Winner B150 Kitcopter

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 maximum all-up-mass *AUM* of the helicopter has been estimated to be around 700 kg, which is acceptable for 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.

2. MAXIMUM GROSS WEIGHT ESTIMATION

Before sizing the main and tail rotors, a good approximation of the helicopter Maximum Takeoff Weight *MTOW* is indispensable. [1-3] allowed to investigate the impact of several components on the total gross weight iteratively. A parametric study derived that for a given useful load *UL* the main rotor speed N_{MR} and radius R_T strongly influence the helicopter gross weight (Fig. 2). The lower N_{MR} and the smaller R_T, the lower the helicopter gross weight. The use of OTS gearboxes imposed a main rotor speed of 517 RPM. Aerodynamic research set limits to the minimum radius, which amounts to 3.7 m. Hence, for the main rotor configuration stated above, the helicopter gross weight figures approximately 680 kg. Consequently, a MTOW of 700 kg at ISA SLS should be made feasible. Figure 3 gives a survey of the weight partitioning according to SAWE RP 7 and 8.

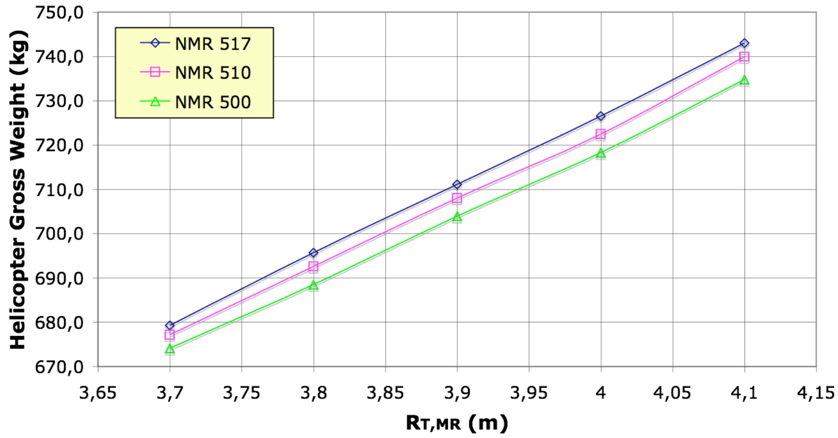

Figure 2 : Influence of main rotor speed N_{MR} and radius $R_{T,MR}$ on helicopter gross weight

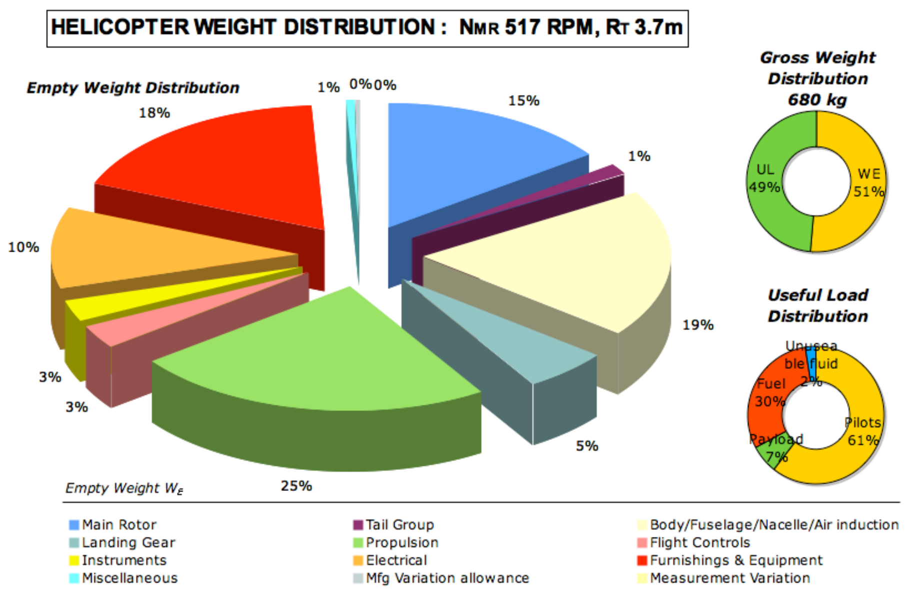

Figure 3 : Gross weight survey, subdivided as recommended by SAWE RP 7&8

3. DRIVE TRAIN ARCHITECTURE AND WEIGHT OPTIMIZATION

The drive train transmits the engine power towards the main and tail rotor and makes them work at the required rotational speed. There exist several ways of doing this job, though, only a few will support a weight friendly solution. Figure 4 explains the contemplated drive train architecture for the Kitcopter.

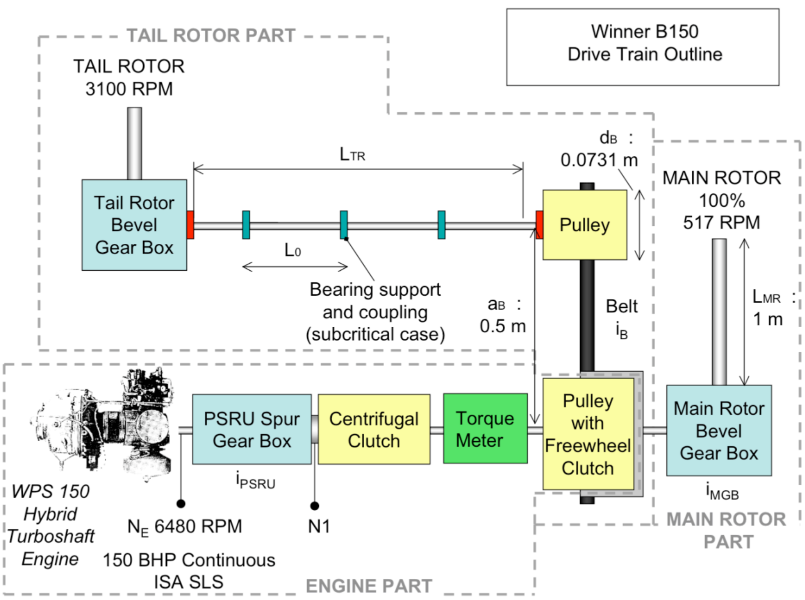

Figure 4 : Sketch of the suggested drive train architecture

A thorough weight optimization study made by Buysschaert and Vanbellinghen [4] showed the necessity to split up the drive train into three parts: an engine part, a main rotor part and a tail rotor part. These parts account for the propulsion, main rotor and tail groups defined by the SAWE RP 7&8. The optimization 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.

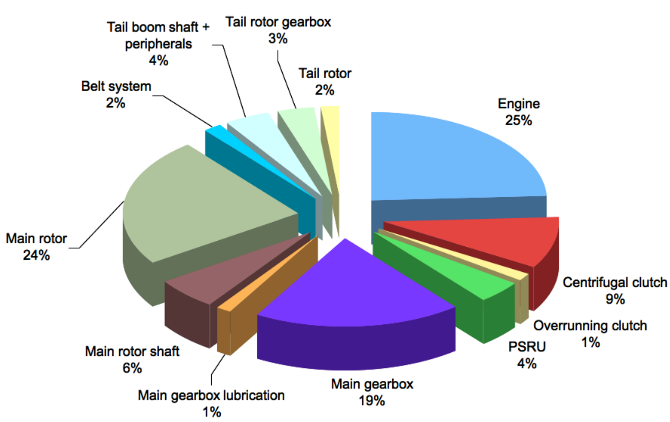

Figure 5 : Subcritical drive train system weight survey

The study unveiled that 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 on the helicopter handling qualities is subject of further research. 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 0.6% of the helicopter gross weight. Figure 5 represents a survey on the weight partitioning of the subcritical drive train system weight.

4. MAIN ROTOR

4.1 Main rotor architecture

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 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 will not incorporate taper. 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.

Figure 6 : Robinson R22 articulated teetering rotor

For a low mass helicopter, a two bladed teetering rotor (Figure 6) 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
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.

4.2 Main rotor characteristics

Rotor radius, chord length, blade quantity, tip Mach number, blade twist and blade weight all have a significant impact on main rotor and thus helicopter performance, drive train system weight and efficiency, engine power requirements, helicopter dimensions and therefore overall weight. After consulting the rotor manufacturer, the main rotor dimensions were set (Table 1). Rarely the helicopter flies at MTOW. Hence, the helicopter gross weight at which the rotor must perform within specifications can be chosen somewhat lower than the suggested gross weight of 680 kg. Here, one puts forward 650 kg.

Table 1 : Main rotor configuration characteristics

Radius R_T (m)	3.7
Main rotor speed N_{MR} (RPM)	517
Chord c (m)	0.196
Minimum load factor ISA SLS, Hover OGE (Thrust-to-Weight-ratio) $n_{LF,min}$ (-)	1.8
Root cutout factor $x0$ (%)	7.7
Blade twist $\theta_{tw,m}$ (°)	-8
Number of blades N_b (-)	2
Polar moment of inertia estimation I_p (kgm^2)	160

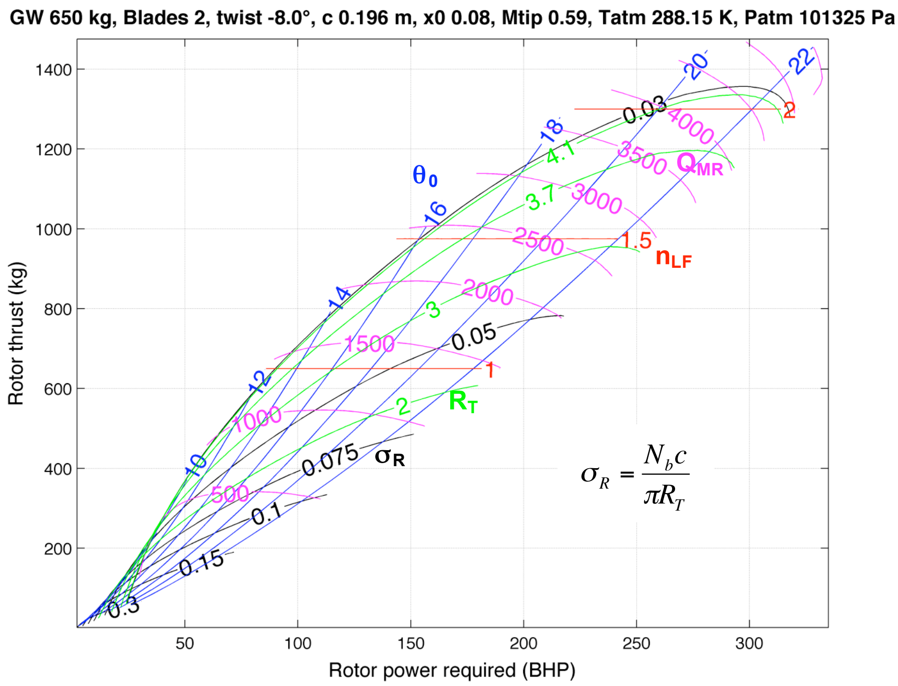

Figure 7 : Main rotor hover chart, OGE, ISA SLS

Figure 7 shows the dimensionalized OGE hover map of the main rotor in hover, OGE for ISA SLS conditions and calculated by a Blade-Element-Momentum-Theory (BEMT) program. Some important results are summarized in Table 2.

Table 2 : Main rotor configuration characteristics, some important results
Design AUM : 650kg Hover OGE ISA SLS

Main rotor power required P_{MR} (BHP)	98
Main rotor torque required Q_{MR} (Nm)	1400
Main rotor maximum load factor $n_{LF,max}$ (-)	1.85
Hub blade pitch angle θ_0 (°)	13.9

One can conclude that the main rotor fulfils the load factor requirement for the AUM of 650 kg. The suggested MTOW of 700 kg lies well within the range of the rotor.

[5] allows to establish a qualitative impression of the main rotor autorotational capability (Figure 8). The energy factor h, the usable energy level ΔEu, the autorotatative index A_i and the autorotation landing index t/K are plotted on Figure 8, among values of other albeit heavier helicopters, with :

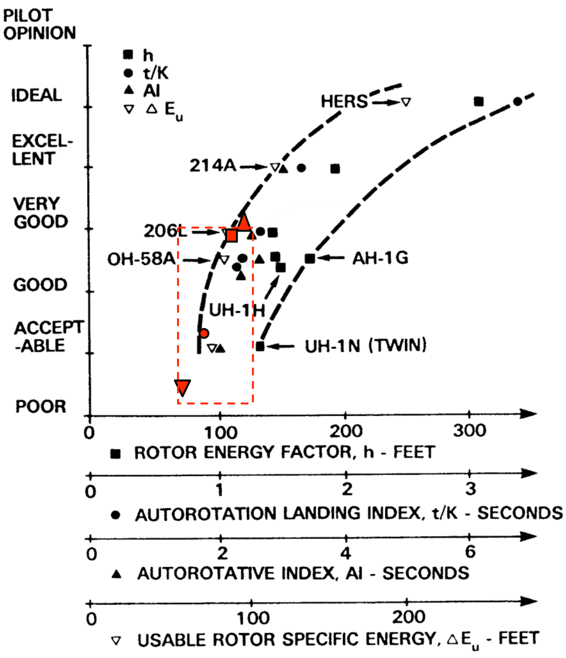

Figure 8 : An approach to the autorotational qualities of the contemplated main rotor

$$h = \frac{I_P \Omega_{MR}^2}{2MTOW}$$

$$\Delta Eu = h\left(1 - \frac{1}{n_{LF,\max}}\right)$$

$$A_i = \frac{I_P \Omega_{MR}^2}{P_{Total,Hover,OGE}}$$

$$t/K = A_i\left(1 - \frac{1}{0.8 n_{LF,\max}}\right)$$

Though h and A_i look very promising, their vertical position may vary inside the dotted box in between the dotted lines. Qualitatively, it looks interesting to reconsider the amount of lead inserted into the blades to increase the energy level in the rotor, and enhancing the autorotational performance of the helicopter, in spite of increasing the main rotor mass.

5. TAIL ROTOR

For preliminary design purposes, a good estimate for the tail rotor diameter results from the correlation suggested by Prouty [6] (Fig. 9). The correlation seems to be of value when comparing the result for the kitcopter with similarly sized helicopters. Applying the trend, the tail rotor diameter D_{TR} for the MTOW of 700 kg and a R_T of 3.7 m approximates 1.2 m.

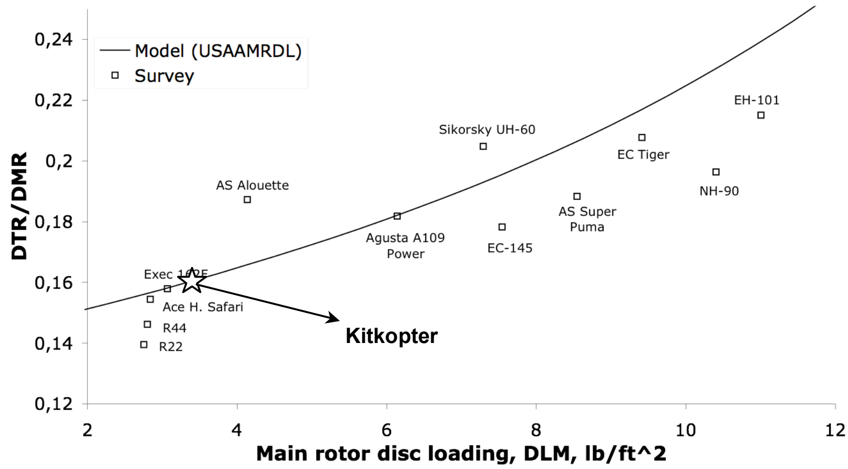

Figure 9 : Tail rotor diameter sizing trend

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} should be equal or less than the vertical distance between the main rotor shaft and the outermost horizontal tail rotor tip position. Hence, the tail boom length L_{TR} should now amount to 4.3 m. Remark that L_{TR} may be longer or smaller, but for the latter case, both rotors cannot collide during any flight condition. For this paper, L_{TR} is set to 4.3 m.

6. WPS-150 HYBRID TURBOSHAFT ENGINE

The heart of the helicopter consists of a 150 BHP[1] 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

Table 3: 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.

[1] Maximum continuous power, International Standard Atmosphere (ISA), Sea Level Static (SLS)

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 10 shows a cutaway of the engine, while Table 3 summarises some important engine characteristics.

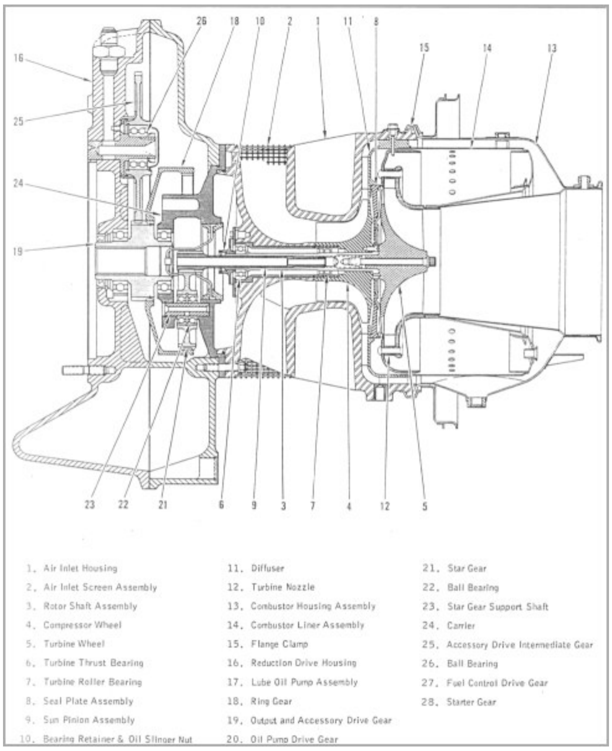

Figure 10 : Solar turboshaft engine cutaway

7. PERFORMANCE CHARACTERISTICS

7.1 Hover OGE

Knowing the dimensions of the main and tail rotor and their rotational speed, the total power requirement, which the engine must deliver, incorporating drive train losses, aerodynamic interference losses and electrical power production, can be estimated. The available power from the engine changes with atmospheric temperature and pressure. A mechanical flat rating power of 150 BHP applies to the engine. However, the engine EGT cannot surpass 638°C. For hot and high conditions, the latter limit restrains the power output of the engine. Hence, the maximum available engine power and total helicopter power requirement, both influenced by the atmospheric conditions, determine the hover OGE flight envelope. Changing the AUM of the helicopter increases or decreases the helicopter power requirements, which in turn influences the OGE hover flight envelope.

Consider ISA SLS OGE hover conditions for the suggested main rotor configuration. Figure 11 shows that the maximum weight the rotor could pull amounts to 730 kg. The MTOW figures 700 kg, leaving thus sufficient power available for transition into another flight regime. Figure 12 shows similar results, but now for hover at 5000 ft, ISA +20°C. For sustained hover, the AUM of the helicopter should then not be higher than 600 kg. Since the empty weight of the helicopter cannot be changed, less useful load will be allowed (lighter pilots, less cargo or fuel). Table 4 gives a resume of 3 important flight specifications, postulated by Winner scs.

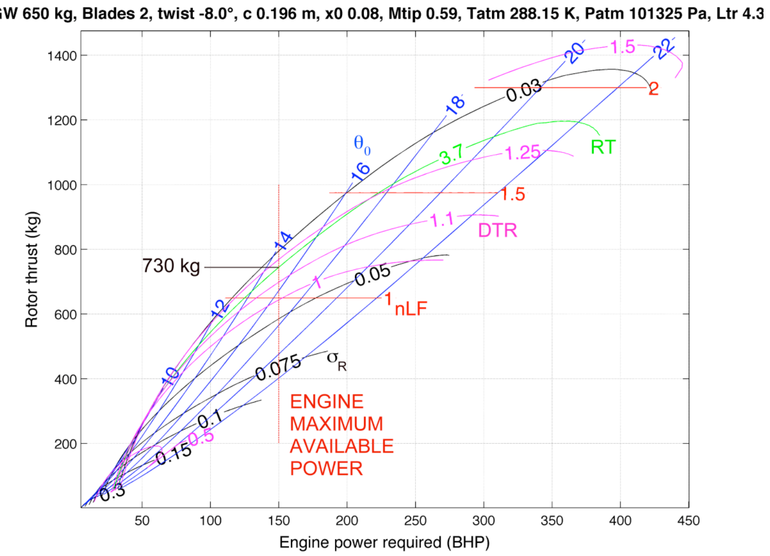

Figure 11 : OGE Hover Chart ISA SLS, Total Power

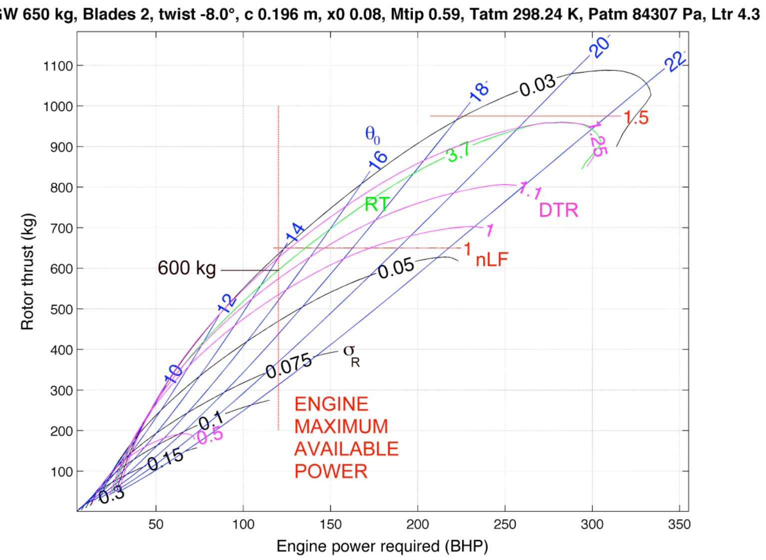

Figure 12 : OGE Hover Chart ISA+20°C 5000 ft, Total Power

Table 4 : Minimum kitcopter operational conditions, Hover OGE

	AUM (kg)	Altitude (ft)	Temperature (°C)
ISA SLS Conditions	700	0	ISA SLS
Hot and High	640	5000	ISA+10
Hot and High	600	5000	ISA+20

7.2 General performance characteristics and global survey

Some provisional performance characteristics were derived for the helicopter configuration stated in the former paragraphs (Table 5). The Kitcopter performance is comparable to that of its prime competitors, though, offering the advantage of a gas turbine engine : lower weight, reduced vibrations, higher degree of reliability and possibly a lower fuel cost. Also, one avoids the use of a carburetor, circumventing issues such as a large susceptibility to icing.

Table 5 : A global survey on the Kitcopter characteristics and a comparison with its competitors

	Kitcopter T150	*Rotorway Exec 162F*	*Ace Helicopters Safari*
Specifications			
Engine	WPS/Solar T62T-150 150 BHP	RI 162F 150 BHP	Lycoming IO-360- M1B / 160-180 BHP
Seats	2	2	2
Gross Weight (kg)	680 (650)	680	680
Empty Weight (kg)	350	442	454
Useful load (kg)	330 (300)	238	226
Fuel Capacity (kg)	160	51.2	84.8
Dimensions			
Overall length (m)	9.20	9.00	9.17
Height (m)	2.43	2.40	2.43
Main Rotor Dia (m)	7.4	7.60	7.90
Tail Rotor Dia (m)	1.20	1.20	1.22
Cabin Width (m)	1.25	1.10	N/A
Performance ISA			
Hover ceiling OGE (ft)	4750	5000	N/A
Hover ceiling IGE (ft)	7550	7000	7000
ROC (ft/min)	1500	1000	1000
Service Ceiling (ft)	TBD	10000	10000
$V_{max\ SLS}$ (kts)	91	100	87
Max. range (km)	400+	290	400
Endurance (h)	2+	2	N/A

8. CONCLUSION

The ongoing study on the development of a two-seat turboshaft equipped kitcopter for the company Winner scs is very promising. The use of OTS components supports the feasibility of the project, though puts in some way constraints on the optimum design of the helicopter.
A parametric gross weight study allowed for a good estimation of the Kitcopter MTOW and the main rotor design AUM. The weight of the helicopter has been shown influencing the rotor power consumption directly. Hence, one should strive for a maximum weight reduction. The drive train of the helicopter should merit special attention, since it represents a major share of the total weight.
A BEMT calculation program, of which the input parameters are defined by the operational conditions, allowed to verify the rotor performance and determined the total required power. Several boundary conditions exist, effectively constraining and consequently defining the main rotor and tail rotor configuration. One has found a suitable turboshaft gas turbine engine, which copes with the total power requirements linked to the design specifications.
The performance of the kitcopter has shown to be comparable to its nearest competitors, though offering the advantage of a gas turbine engine.

ACKNOWLEDGEMENTS

The authors sincerely thank J. Joordens from the company Winner scs for his continuous technical and financial support and the fruitful discussions. They want also to thank the DGTRE (Walloon Region) for supporting this development activity.

REFERENCES

[1] SAWE Recommended Practice 8 (RP8), *"Weight and Balance Data Reporting Forms for Aircraft (including Rotorcraft), Revision A"*, Society of Allied Weight Engineers, Los Angeles, United States of America, June 1st 1997.

[2] J.A. Crabtree, *"Weight estimation for helicopter design analysis"*, Proceedings of the 17th National Conference of the Society of Allied Weight Engineers, New York, United States of America, 1958.

[3] C.L. Landers, L. Lucero and K.D. Henthorn, *"Helicopter Preliminary Design"*, Proceedings of the 60th Annual Conference of the Society of Allied Weight Engineers, Arlington, Texas, United States of America, 2001.

[4] F. Buysschaert, D. Vanbellinghen and P. Hendrick, *"Weight estimation of a two-seat turboshaft equipped helicopter transmission drive system"*, Proceedings of the 66th Annual Conference of the Society of Allied Weight Engineers, Madrid, Spain, 2007.

[5] AGARD Report No. 781, *"Aerodynamics of Rotorcraft"*, AGARD, France, 1990.

[6] AIAA Aerospace Design Engineering Guide, 5th edition, September 2003.