CONVENTIONAL HELICOPTERS AND THEIR ADAPTIVENESS FOR MORE ELECTRIC AND ALTERNATIVE TRANSMISSION TECHNOLOGIES

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ABSTRACT

The powerplant and drive systems in a conventional helicopter cause high development and operating costs, compromise safety and introduce performance limitations. Even though much effort is devoted to mechanical transmission systems, the use of electric components promise a higher reliability. The use of magnetic gearboxes proved too heavy, however, the possibility of electric motors to drive the tail rotor is possible at the expense of weight. The use of liquid hydrogen in a helicopter seems feasible, though heavier due to an increased helicopter volume and tank weight, while it offers a free cold-source for high-performing HTS devices.

KEYWORDS

COST, SAFETY, TRANSMISSION, ALTERNATIVE, SR-MOTOR, HTS, MORE-ELECTRIC, HYDROGEN

1. INTRODUCTION

Three pillars support the success of a helicopter product : performance compliance, cost efficiency and safety. If one of those pillars fails, it will be difficult for the product to get commercialised or assure competitiveness with other products. Metaphorically speaking, during the life of a helicopter, the three pillars are regularly scaffolded and need constant examination. Faults appear all the time, some are product related, while others may be ascribed to the concept. For example, rotor compressibility and stall effects introduce difficulties to increase the maximum forward flight speed for helicopters with a single main rotor [1], while the mechanical transmission is a source of vibrations and an important source of failures and malfunctions [2]. Besides the three pillars supporting success, a fourth important factor plays a role, which is the flexibility for modifications, viz. adaptiveness, of a concept and its systems. Without this characteristic, the concept will not stand against the technological evolution, eventually die on the vine. The concept reviewed in this paper is the conventional helicopter with single main rotor and tail rotor. Possible reasons requiring concept flexibility are the introduction of substantial technology changes, e.g. the use of more reliable, more powerful and more cost efficient systems, which must be "integrable" in the concept. Particularly in the airplane industry, a significant amount of attention is given to more-electric solutions. Principally, they are expected to noticeably reduce Life Cycle Costs (LCC) [3]. Another example is the flexibility to use other fuel types, such as hydrogen, an in the contemporary greenhouse and fuel depletion context frequently examined energy carrier for future air transport systems.

All four facets will now be discussed in the next two paragraphs, starting with an exploration of cost driving and safety compromising components in a conventional helicopter. Then, their influence on helicopter performance will be discussed, after which one will propose and evaluate alternative technologies on a conceptual level.

2. COST, SAFETY AND PERFORMANCE

2.1 Cost

The Life Cycle Cost (LCC) is a frequently used parameter to reflect the total cost from purchase to retirement of a rotorcraft. It is a yardstick for the financial competitiveness of a rotorcraft [4][5]. Two major parties are subject to LCC : the manufacturer and the operator. One subdivides the expenses of the manufacturer in *non-recurring* and *recurring costs* [6], where the operator expenses are regularly classified under *direct (DOC)* and *indirect (IOC) operating costs*

[4]. When comparing the cost effectiveness or "fitness" of a system or component in a helicopter, the manufacturer's recurring costs and direct operating costs merit most attention. Indeed, the manufacturer non-recurring costs can be strongly influenced by the type of project under which the development falls, sometimes leading to much cheaper spin-off versions resulting in an unreliable basis for comparison [7]. Although the indirect operating costs can account for 44-55% of the bill [8], they are not related to the helicopter from a technical point of view. [9] confirms this, explaining that manufacturers use the direct operating costs frequently to compare the impact of various technology levels. The manufacturer recurring cost and the direct operating costs are now examined more closely, i.e. on a component level.

2.1.1 Manufacturer recurring costs. [6] explains cost estimation relationships (CER) based on Weight Estimation Relationships (WER) of component groups as suggested by SAWE RP8 (Table 1). These CER were put in a MatLab model in order to examine the influence of these component groups on the total manufacturer recurring cost, for several production volumes Q and Design Gross Weights W_g.

[6] subdivides the manufacturing recurring costs in assembly and production costs, respectively C_{RA} and C_{RP} :

$$C_{RP} = \sum_{k=1}^{18} C_{RP,k} \quad (1)$$

$$C_{RA} = 5.325\left(\sum_{k=1}^{18} C_{RP,k} - \sum_{k=7A,10,14} C_{RP,k}\right)Q^{-0.3959} \quad (2)$$

where k represents the group number. C_{RA} and C_{RP} are cumulative average costs for a production volume Q, since a learning effect needs to be accounted for. The sum of (1) and (2) gives finally the manufacturer recurring costs CAC_{RM} :

$$CAC_{RM} = k_{CPI}(C_{RP} + C_{RA}) \quad (3)$$

with k_{CPI} a correction factor based on the Consumer Price Index (CPI), taking inflation into account [5]. Where necessary, the WER were modified to fit better the contemporary trends. These were studied by one of the authors.

Figure 1 shows a relative cost distribution for all component groups. Besides the assembly costs, the propulsion system takes an important share. Whereas the influence of the assembly costs on the total cost diminish with increasing production volume Q, the relative propulsion system cost keeps rising. On the

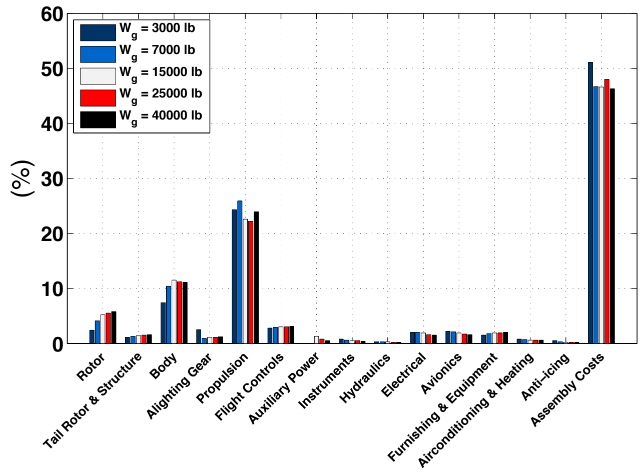
TABLE 1 : Group classification used by [6]

Group number k		**Name**
1		Wings
2		Main rotor
3		Tail rotor
4		Fuselage
5		Alighting gear
6		Nacelle
7	(A,B,C)	Propulsion
8		Flight controls
9		Auxiliary power unit
10		Instruments
11		Hydraulics
12		Pneumatics
13		Electrical
14		Avionics
15		Furnishings and Equipment
16		Air-conditioning
17		Anti-icing
18		Load and handling

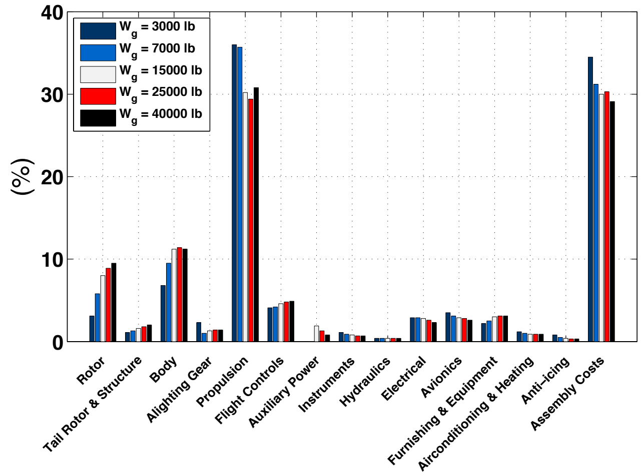
one hand, the reduction of assembly costs drives up the importance of the production costs, but on the other the propulsion system appears to be less susceptible to the positive influence of the learning curve compared with the other component groups, the reason of which one could deduce by the high complexity of the system. The effects of Design Gross Weight remains minor, except for the rotor and fuselage (body) groups. The heavier the helicopter, the more complex and costly they become, explaining their increase of relative importance.

As indicated in Table 1, the propulsion system can further be subdivided into the powerplant (A), drive (B) and fuel (C) subsystems. As a rule of thumb, the powerplant subsystem -mainly consisting of the engine and its peripherals-, takes about 70% of the propulsion system production costs, while the drive subsystem -i.e. gearboxes, lubrication systems, shafts, etc.- 30%. The fuel subsystem cost can be seen as negligible.

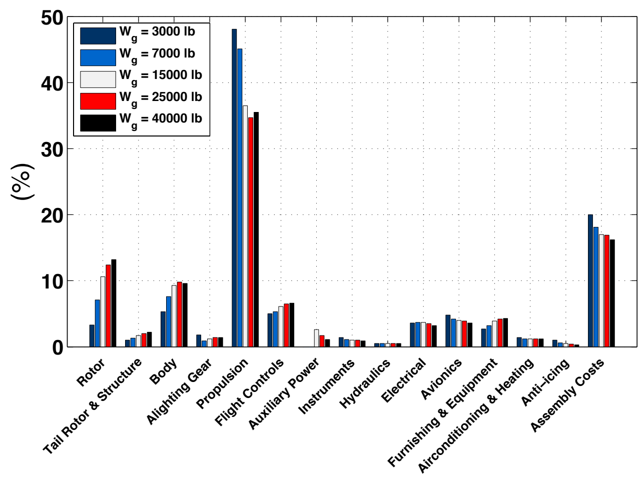
2.1.2 Direct operating costs. Standing charges, maintenance and flight operations contribute to the DOC. [10] notes that 50% of the DOC is engine related, which also includes fuel cost. But if it comes to the "fitness" of a component placed in a helicopter, it is more sensible to observe the required maintenance costs and actions to keep it operational. [11] states that the rotor drive system stands for 25% of the direct maintenance cost (DMC), wherefrom 40% on an unscheduled basis. The maintenance



(a) $Q = 10$ units



(b) $Q = 100$ units



(c) $Q = 1000$ units

FIGURE 1 : Relative cumulative average cost represented for the discussed helicopter component groups.

actions had to address primarily gear-wear and leaks. In another study done by [2], engine and transmission components were identified as prime maintenance cost drivers, up to 62% in total. Vibrations were hereby indicated as the major responsible.

2.1.3 Concluding notes. In the former two paragraphs, the propulsion system and more specifically the engine, transmission and rotor emerged as important cost drivers from a constructional as well as an operational viewpoint. Indeed, these components have a complex nature and while this invokes high manufacturing costs, they require sufficient care in order to continue functioning properly. Also, there appears to be a strong causal relationship between vibrations and maintenance costs, while vibrations are inherently related to the primary components in the helicopter, viz. the engine, transmission and rotor.

2.2 Safety

For reasons of airworthiness, all aircraft must undergo a certification process. Although made to pursue the highest reasonable safety standards, accidents still occur. During the last decade, the NTSB (National Transportation Safety Board) unveiled an average helicopter accident rate of 15.1 per million flight hours, of which 18% were fatal. Several elements influence the accident rate. [12] indicates the importance of the region wherein the activities take place (Fig. 2), while [13] shows the impact of the type of operation (Fig. 3).

From NTSB data of the last decade, including [12], a survey on the *first occurrences leading to accidents* was established. These are the first *technical* malfunctions in a chain of mishaps/failures, eventually leading to an accident. About 50% can be associated with loss of control and engine(s). Others consist of collision (21%), weather (12%) and structural (9%) related failures. What is remarkable is that airplanes flying under the same operation regulations, i.e. FAR Part 135 “On Demand”, show a 10% lower failure rate in the engine and control classes, where more than half of the aircraft use piston engines.
The above mentioned issues do not reveal the initial cause that led to the first occurrence, which can be - and usually is- a human error (piloting, maintenance, etc.), but it implicitly refers to conceptual weaknesses, as the helicopter operations exhibit a higher accident rate than airplanes of the same operations category, while unveiling explicitly the technical categories subject to the highest failure ratios, viz. the engine(s) and the control related components/systems.

Finally, the flight phase deserves some attention (Fig. 4). During Take-off & Climb, Approach & Landing and Manoeuvre & Hover, 61% of the first occurrences emerge. During these flight phases, the engine(s) and controls are highly loaded. An important system which has not been explicitly mentioned by the safety agencies is the transmission system, which is during these phases -if not all- under significant dynamic loads and of critical importance. Since the transmission system has already been identified as a major cost driver in the former paragraphs, and seen its complexity and relationship with the engines and control of the rotorcraft, its

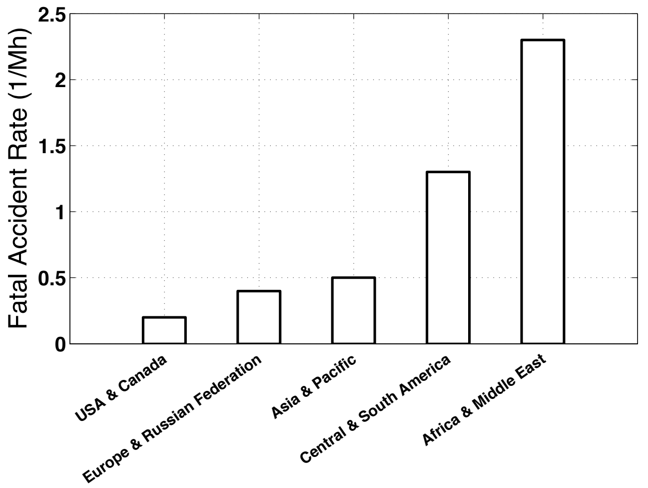


FIGURE 2 : Impact of geographic location of operations on accident rate per million of flight hours.

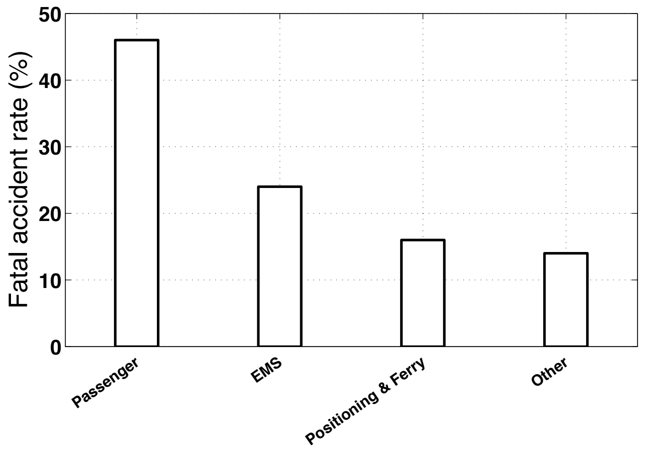


FIGURE 3 : Survey of first occurrence technical failures.

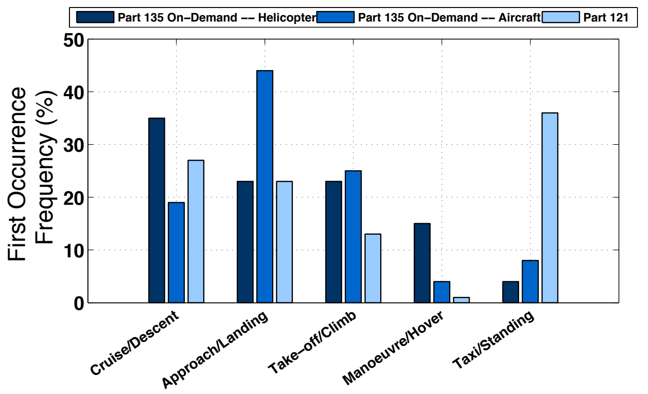


FIGURE 4 : Influence of flight phase on first occurrence.

impact on the total reliability of the helicopter should therefore be regarded as important - if not vital.

2.3 Performance

According to the Thesaurus dictionary, performance means *"the capabilities of a machine or product, especially when observed under particular conditions"*. Clearly, a well performing helicopter is one capable of fulfilling the requirements for which it was designed. However, a product can be well performing in its own niche, but score inadequately compared to other products designed under other requirements. This comparison makes sense when comparing helicopters with airplanes. Airplanes have a higher lift-to-drag ratio, making them physically more efficient. In spite of this, the advantages that vertical lift-off and landing capabilities offer set many minds dreaming [14] and keep on driving scientists and experimentalists to find the ultimate machine. Unfortunately, this machine still needs to be invented as "well performing" demands also a reasonable cost-friendly and safe solution.

Generally, *conceptual* and *mechanical* limitations introduce performance constraints, which is especially true for the helicopter configurations we know today. Speed plays an important role in the productivity of an aircraft[1][14], viz. the faster a payload can be transported, the more the aircraft can deliver in a given amount of time. Although the impact of increasing speed on operating costs can become significant [1], helicopter research always pushes the speed boundaries in order to enhance the helicopter performance envelope and become more competitive with airplanes.

Unfortunately, blade stall and advancing blade compressibility effects limit the maximum speed of a rotorcraft. These phenomena originate from the physical and thus *conceptual* nature of the helicopter i.e. with a "horizontally" placed rotor with respect to the free stream airflow. A better understanding of rotor blade aerodynamics (e.g. BERP [15]), the introduction of conceptual modifications such as compounding [16] (Lockheed AH-56 Cheyenne), coaxial rotor variants [16] (Sikorsky S-69, X-2), variable speed rotors (Boeing A160T [17]), etc., continuously offer solutions (the one more cost effective than the other) to further expand the speed envelope. A remarkable rotorcraft was the tip-jet-and outboard-engine driven Fairey Rotodyne establishing a new closed-circuit world speed-record in 1959 [18]. The project was unfortunately terminated in 1962 due to lack of support and since it was government property, the aircraft was by rule destroyed.

Other performance boundaries are imposed by the *mechanical* limitations in a conventional helicopter. Most noteworthy are the powerplant and drive subsystems in the propulsion system, which already passed the cost and safety review, and where they showed concern. These subsystems are typically *"flat rated"* while designed for maximum power densities, which is not unusual as the propulsion group represents about 20% [6] of the total Gross Weight, making it the heaviest system in the helicopter. According to [19], the drive subsystem performance strongly impacts the helicopter performance, while needing continuous improvements in the domain of safety, reliability, efficiency, vibrations and acoustic noise. This is especially true for the main gearbox. Hereby, one must strive for maximum efficiency as the temperature monitoring in the gearbox has a non-negligible impact on the rotorcraft Empty Weight [20]. While multi-stage planetary or epicyclic gears exhibit stage efficiencies over 99% [20], enhancements and other concepts emerge such as the *Self-Aligning Bearingless Planetary Gears* (SABP) [21][22] claiming a weight and noise reduction over the traditional planetary gearbox thanks to the absence of planet gear bearings and carriers, *High Contact Ratio Gears* (HCR) [23] causing a noise and weight reduction due to lower dynamic loads, and *Split-Torque Transmissions* splitting the power load-path over multiple gears without the use of any epicyclic gear stages [24][25] resulting in an improved reliability, weight and gearbox efficiency. A remarkable result was obtained with hydrostatic worm-gearing, as explained by [26]. Here, each engine is connected to a worm, which in turn drives a common centre gear (worm gear) connected to the main rotor. Thanks to an oil film squeezed between worm and gear, the impact of the high relative velocity between the inter-meshing planes can be largely reduced. The configuration allows reduction ratios over 100 with an efficiency beyond 99% while saving 59% in weight over a conventional architecture. Due to the high weight savings, the hydrostatic worm-gearing concept was introduced in the adaptiveness study discussed in the next section. It is not clear however why this system has not found any further endorsement, or why no more documentation was available. Table 2 gives a general survey of the system developed for a helicopter with a Gross Weight of 31 metric tons with 3 engines producing 4000 kW each.

TABLE 2 : Hydrostatic worm gearbox characteristics [26]

Mass†	1151 kg
Power density (mass weighed†)	10.4 kW/kg
Power density (volume weighed‡)	0.22 kW/cm^3
Efficiency	99.14%
Pump oil pressure	350 bar
Oil flow	39 L/min

† Complete gearbox, including sumps and pumps.

‡ Volume of 3 worms with bearings and worm gear only.

3. CONCEPTUAL ADAPTIVENESS

In the previous sections, the propulsion system, and especially its powerplant and drive train subsystems, outlined important cost, performance and reliability concerns. This section explores alternative technologies, which could replace some parts of the propulsion system, while examining their integrability in a helicopter environment, or seen from another perspective, the adaptiveness of the helicopter to allow other technologies to be installed without compromising cost, safety and performance.

The propulsion system technology is strongly bound to the type of energy carrier selected for implementation. Several of them will be overviewed.

Electrical locomotion is continuously gaining importance in the transportation sector, where one strives for the best results with regard to cost, performance and reliability [27]. Therefore some emerging electric technologies deserve attention.
Here, the following new "electric" technologies and their integrability on a helicopter will be studied : magnetic gears, switched reluctance motor and high-temperature-superconductive devices. Afterwards, a few interesting configurations applying some of these novel technologies will be put forward and examined on a conceptual level.

3.1 Alternative gearboxes : the magnetic way

Magnetic gearboxes use magnetic forces instead of "mechanical" forces to transmit mechanical power in addition to achieving a speed reduction. An industrial solution became feasible thanks to the use of powerful rare-earth magnets such as $SmCo_5$ and NdFeB. [28] and [29] mention advantages such as lower acoustic noise, less vibrations, more reliable, less maintenance, ease of manufacturing, inherent protection against overload (protecting the expensive powerplant against over-torquing or overheating), robustness and no physical contact between input and output shafts. In fact, these characteristics would deal with many of the problems encountered in mechanical gearboxes.
Early magnetic gearbox architectures resemble the mechanical counterparts significantly, with for example spur [30], spiral [31], bevel [32] and worm [30] configurations, but their specific torque-densities ϱ_τ remained poor (Table 3). Newer designs were noticeably improved, with the concentric magnetic gear, magnetic planetary gear, cycloid permanent magnet gear (Fig.5) and magnetic harmonic gear. Downside of these technologies is weight and the current level of acquired reduction ratios, possibly requiring multiple stages. Even though [33] states that the required volume is commensurate with torque, the average density of 8000 kg/m^3 [34] remains excessively high.

A benchmark for the magnetic torque transfer capabilities is, according to [34], the torque coupler, having a 1:1 reduction ratio. The cycloid permanent magnet gear exhibits a specific torque-density which is twice as low as the torque coupler, meaning there is still room left for improvement, while weighing three times as much as the usual mechanical gearbox. Also, the efficiency turns out to be lower than those observed with a mechanical transmission (up to 7%, Table 3) and the magnets should be kept at operating temperatures below 300°C at all times to avoid demagnetisation [37]. Nevertheless, it must be noticed that the reduction ratio of one stage corresponds to the required reduction between turboshaft and main rotor, as indicated on Figure 10 (lower W_g-class).

It is therefore necessary to monitor the feasibility on a helicopter which must be investigated. For conceptual purposes, a good verification parameter is the relative importance of the magnetic gearbox weight with respect to the helicopter Gross Weight W_g. The maximum transmitted torque is here estimated by :

$$\tau = \frac{P_{MTOP} \cdot R_{tip,MR}}{V_{tip,MR}} \quad (4)$$

using the *Maximum Take-off Power* P_{MTOP}, the *main rotor radius* $R_{tip,MR}$ and the *main rotor tip speed* $V_{tip,MR}$ as defined by equations (5-7), originating from a general helicopter survey and all function of helicopter Gross Weight W_g (Fig. 6-8) :

$$P_{MTOP} = 0.0680 W_g^{1.1693} \qquad \text{[kW][kg]} \quad (5)$$

$$R_{tip,MR} = 0.4097 W_g^{0.3274} \qquad \text{[m][kg]} \quad (6)$$

$$V_{tip,MR} = 215 \qquad \text{[m/s]} \quad (7)$$

Applying the average density as discussed by [34], one retrieves the weight fractions of the above-mentioned magnetic gearbox types with respect to helicopter Gross Weight. Whereas the mechanical gearboxes represent only 10% of the Gross Weight, the magnetic gearboxes turn out to be heavy (Fig. 9). For the lower segment of Gross Weights, the lower power requirements and the smaller blade radius result in lower torque on the shaft, which eventually leads to lower magnetic gearbox weights. The mass of the best configuration, i.e. the cycloid permanent magnet gear, ranges from twice to tenfold the mass of the mechanical transmission system, which is already considered as too heavy. Thus, it appears unwise to

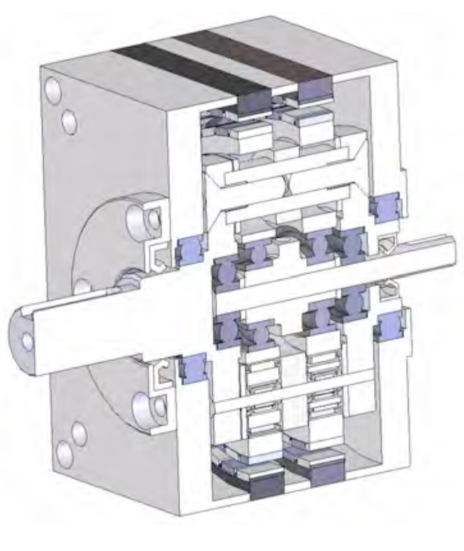


FIGURE 5 : Courtesy of F. Jørgensen

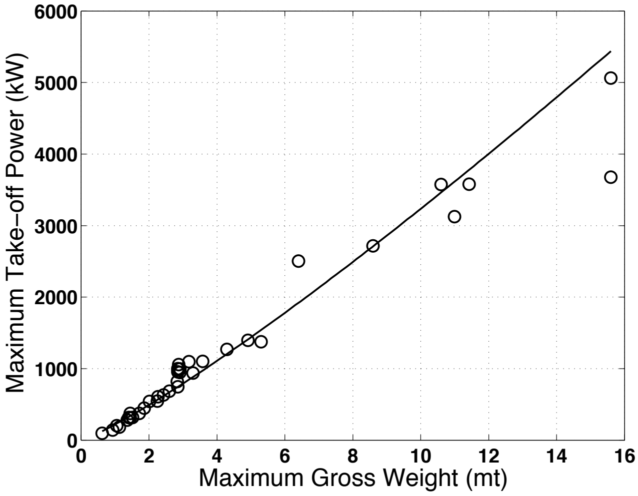


FIGURE 6

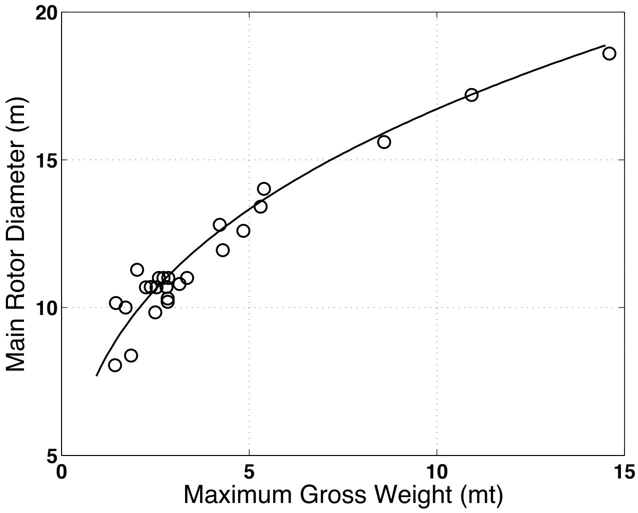


FIGURE 7

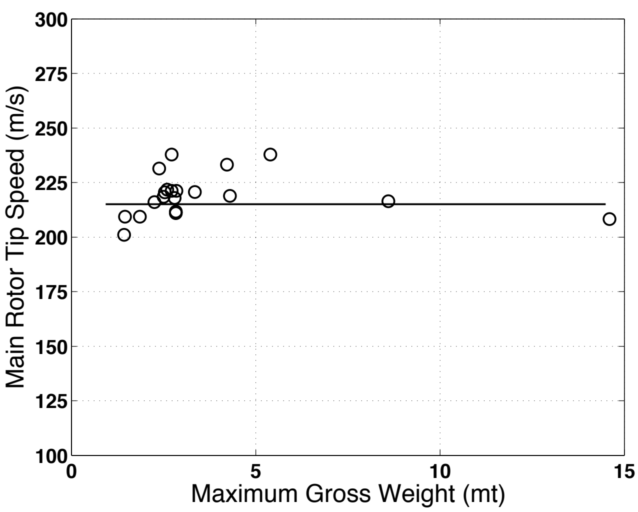


FIGURE 8

TABLE 3 : Characteristics of magnetic gearing devices

Type	ϱ_τ[kNm/m^3]*	Reduction	Efficiency†
Magnetic worm (MWM) [30]	0.1	33:1	-
Spiral magnetic gear (SMG) [30]	1.7	3:1	-
Concentric magnetic gear (CMG) [34]	92	5.5:1	96%
Magnetic planetary gear (MPG) [30]	97.3	3:1	-
Cycloid permanent magnet gear (CYMG) [35]	183	21:1	92-94%
Magnetic harmonic gear (MHG) [36]	110	20+:1‡	-
Torque coupler (MTC) [34]	400	1:1	-

* Observed torque-density ruling on output shaft † Best efficiency (near maximum torque)

‡ Possibility of two stages resulting in a reduction of 860:1 and more

analyse these magnetic gearboxes in a helicopter-integrated environment as most of these systems have a mass in the same order of magnitude of the unmodified helicopter.
It must be noted however that the stated performance characteristics were adopted from small-scale magnetic gearbox prototypes. Hence, torque-density improvements are still achievable. Research should also further optimise gearbox efficiency and examine the maximum reduction ratios per stage.

3.2 Alternative propulsion systems

The success of a propulsion system depends on the combination of powerplant, drive train and type of energy carrier. The best combination delivers the highest *Useful Load to Gross Weight* ratio (UL/GW), where the Useful Load mainly represents the summed mass of payload and fuel. The selection of a turboshaft with kerosene as fuel is currently the general standard. Tables 4-5 give a summary of several energy carriers and energy converters, i.e. engines or motors. From the evaluation that follows, the above selection will appear natural.

3.2.1 Energy carrier selection. An energy carrier delivers the energy to drive an engine or motor. The energy carrier must be stored aboard the aircraft, where volume and weight need to be minimised. The fossil fuels perform well when observing the mass-weighed energy density $\varrho_{E,m}$ and the volume-weighed energy density $\varrho_{E,V}$ (Table 4). However, liquid hydrogen (LH_2) has a $\varrho_{E,m}$ which is about three times larger but exhibits a noticeable twelvefold lower $\varrho_{E,V}$ compared to kerosene.

Electrical power carriers, such as Lithium-Sulphur (LiS) batteries, still lack performance compared to chemical fuels, while being constrained by the limited mass-weighed power density $\varrho_{P,m}$. Indeed, for the lower range of required endurance, more batteries will need to be installed to deliver the required power level, causing an excess of endurance. This is

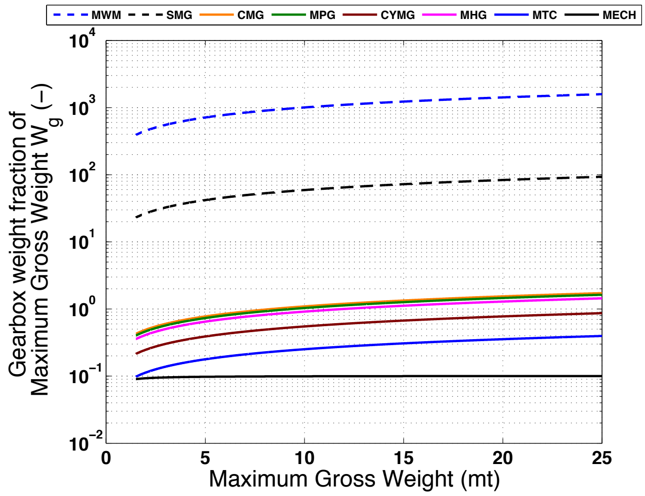


FIGURE 9

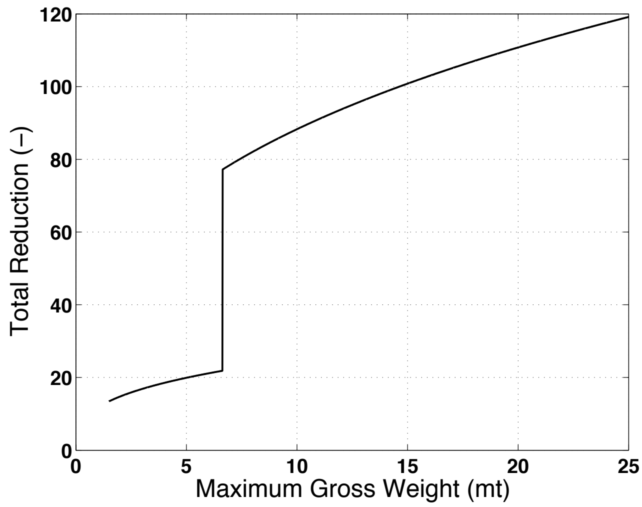


FIGURE 10 : Total reduction between engine output shaft and main rotor, based on survey data.

explained as follows. If P_{req} and T_{req} are the *required power* and *required endurance* respectively, and, E_{req} and E_{mi} respectively the *required energy* and *minimum-installed energy*, then :

$$E_{req} = P_{req} \cdot T_{req} \tag{8}$$

TABLE 4 : Energy carrier performance

Type	$\varrho_{E,m}$	$\varrho_{E,V}$	$\varrho_{P,m}$	ϱ
Chemical				
Kerosene (LHV**) [40]	43.2 MJ/kg	34.7 MJ/L	-	804 kg/m^3
Avgas 100 LL (LHV(**)[40]	43.7 MJ/kg	31.3 MJ/L	-	715 kg/m^3
Bio-diesel (LHV) [41]	38.8 MJ/kg	27.3 MJ/L	-	880 kg/m^3‡‡
Hydrogen (LHV**) [EERE&NIST]	120 MJ/kg	8.51 MJ/L*	-	71 kg/m^3*
Methane (LHV**) [EERE&NIST]	50.0 MJ/kg	21.1 MJ/L†	-	423 kg/m^3†
Propane (LHV**) [EERE&NIST]	45.6 MJ/kg	26.5 MJ/L‡	-	581 kg/m^3‡
Electro-chemical				
Lithium Sulphur Battery [42]	1.26 MJ/kg	1.26 MJ/L	0.2 kW/kg	1.064 kg/m^3
Vanadium Boride Air Cell†† [43]	-	18 MJ/L	-	-
AEROPAK™†† [45]	1.62 MJ/kg	0.89 MJ/L	0.1 kW/kg	548 kg/m^3

* Saturated liquid state : 20K, 1 bar
† Saturated liquid state : 112K, 1bar
‡ Saturated liquid state : 230.74K, 1 bar
** Lower Heating Value : 288.15K, 1 atm
†† Irreversible process, requires partial replacement
‡‡ Average density according to DIN EN 14214

TABLE 5 : Energy conversion elements

Type	$\varrho_{P,m}$	η_{th}
Chemical to Mechanical		
Turboshaft (TS)*	4.2 kW/kg	25%
Diesel Piston Engine (DPE) [44]	1.31 kW/kg	41%†
Piston Engine (PE) (Avgas) [46]	1.0 kW/kg	27%
Electrical to Mechanical		
Switched Reluctance motor (SR)‡	2.2 kW/kg [38]	80...95% [39]
Permanent Magnet motor (PM)**	2.6 kW/kg [47]	88.4% [48]
HTS motor	> 10 kW/kg [50]	94...98% [51]
Chemical to Electrical		
PEM Fuel Cell	1.0 kW/kg [52]	57% [49]

* Average value taken from survey
† 225g/kWh [44] with LHV bio-diesel
‡ Rotational speed of 15000 RPM
** Rotational speed of 10000 RPM

$$P_{req} = m_{mi} \cdot \rho_{P,m} \tag{9}$$

$$E_{mi} = m_{mi} \cdot \rho_{E,m} \tag{10}$$

$$\epsilon_E = \frac{E_{req}}{E_{mi}} = \frac{\rho_{P,m} \cdot T_{req}}{\rho_{E,m}} \tag{11}$$

with m_{mi} the minimum installed mass and ε_E the *Energy Carrier Efficiency*. ε_E larger than unity does not make sense because then there will not be an excess of batteries required to deliver the required power ($E_{req} > E_{mi}$). Figure 11 shows the ratio of *excess mass* m_{ex} to *energy-weighed required mass* m_{req} becoming zero at the *compensated endurance* T_{ce}, where the ε_E becomes unity and no excess mass m_{ex} needs to be installed :

$$E_{req} = m_{req} \cdot \rho_{E,m} \tag{12}$$

$$\frac{m_{ex}}{m_{req}} = \frac{1}{\epsilon_E} - 1 \tag{13}$$

The AEROPAK™, a fuel cell with energy cartridge, clearly shows a less efficient tendency with respect to the LiS batteries ($T_{ce,AEROPAK} > T_{ce,LiS}$).
Chemical energy carriers do not have this issue, hence always having ε_E of unity.

3.2.2 Sustainable energy carriers. The fossil fuel depletion and the greenhouse issues, set many researchers en route to find an alternative well performing energy carrier. Nowadays, there is no consensus of what is the better solution. While some disprove hydrogen as the future energy carrier [53], or

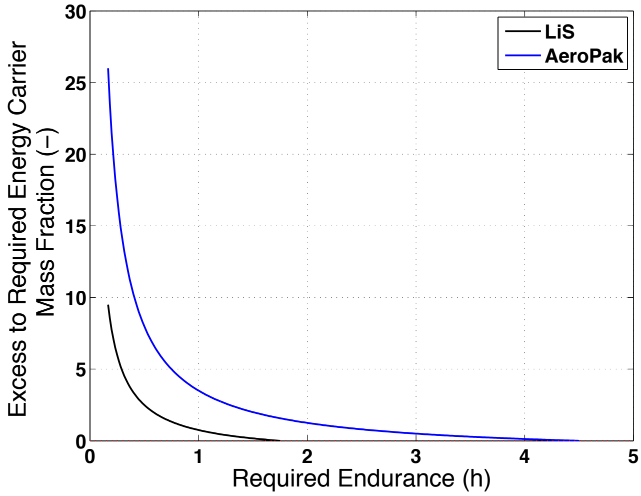


FIGURE 11

believe the helicopter market to remain using carbon-based bio-fuels in a sustainable environment [1], others examine the feasibility of implementing hydrogen in aircraft such as [54][55]. Hydrogen can be produced in many ways, ironically from oil via steam-reforming [56], or via electrolysis. Although delivering hydrogen at the enduser requires about three times the enduser's power consumption [57], the cryogenic storage of hydrogen could provide opportunities using more electric high temperature superconductive devices (HTS), which will be discussed later on.

Before examining the energy conversion elements, some remarks about liquid hydrogen must be made. For safety reasons, only liquid hydrogen (LH_2) allows the installation of a significant amount of energy in a fuel tank. Gaseous hydrogen would require high pressure storage, eventually leading to a heavy tank and explosion risks. The gravimetric efficiency ε_g of a fuel tank intended for LH_2 use is according to [58] 25% :

$$\epsilon_g = \frac{m_{LH_2}}{m_{LH_2} + m_{ft}} \qquad \text{[-] (14)}$$

where m_{LH2} and m_{ft} represent respectively the initial mass of liquid hydrogen in the tank and the mass of the fuel tank.

[58] also derived the optimum maximum or critical operating pressure in a multilayer insulated tank for small aircraft to be approximately 8 bar, keeping 3% ullage to avoid the pressure relief valve to become inoperative, i.e. the valve does not come into contact with the liquid hydrogen fraction. If one takes 1 bar for the tank absolute filling pressure, the tank volume may only be filled with 75% of liquid hydrogen (Fig. 12). Indeed, during flight, heat enters the tank causing the liquid hydrogen to expand and increase in pressure and temperature (Figure 13).

Finally, hydrogen has two molecular forms, i.e. ortho-hydrogen (o-H_2) and para-hydrogen (p-H_2)[59]. The

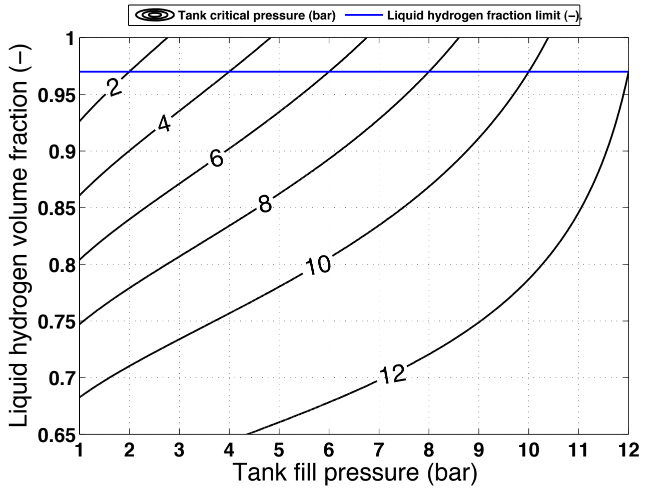


FIGURE 12

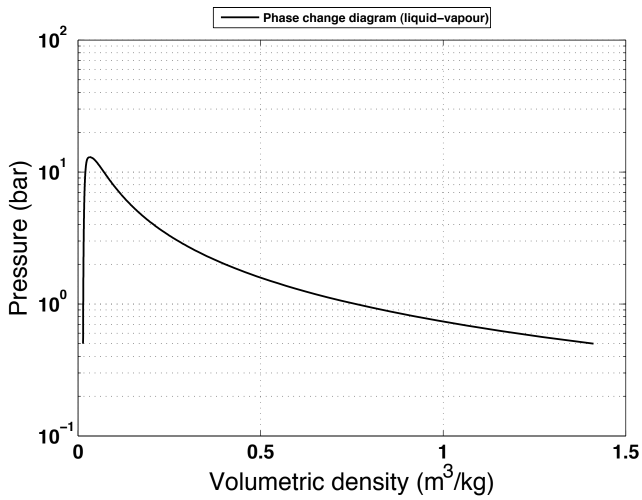


FIGURE 13

difference between both types lays with the spin of the hydrogen nuclei. o-H_2 has nuclear spin vectors in the same direction, p-H_2 has opposing vectors. Both coexist, but their concentration depends on temperature. Liquid hydrogen at 20.3K consists of 99.8% of p-H_2, 0.2% o-H_2. The transformation from o-H_2 to p-H_2 is exothermic. At normal conditions, 75% is o-H_2. Therefore, the LH_2 fuel should already be supplied in its equilibrium state with mainly p-H_2 to avoid an exothermic reaction in the helicopter fuel tank, causing more boil-off and thus losses.

3.2.3 Energy conversion elements. Table 5 summarises important energy conversion elements. Here, for the conventional helicopter, one considers the rotors to be driven mechanically. Thus, several configurations with energy carrier and conversion elements can be made. Table 6 gives a resume of the examined configurations, which will now be investigated qualitatively. Discarding the effects of helicopter mass reduction with time on the required power due to fuel burning, one can state :

$$m_{prop} = m_{ec} + m_{cr} \qquad (15)$$

with m_{prop} the total mass of carrier and conversion elements, m_{ec} and m_{cr} respectively the mass of the energy conversion elements and the mass of the energy carrier. Then, it follows with $P_{m,req}$ the *required mechanical power* :

$$m_{prop} = P_{m,req}\Bigg(\frac{1}{\rho_{P,m,ec}} + \frac{T_{req}}{\eta_{th}\cdot\rho_{E,m,ec}}\cdot \left[1+\left(\frac{1}{\epsilon_E}-1\right)_{\epsilon_E<1}\right]\Bigg) \qquad (16)$$

The last term between brackets in Eq. 16 only appears when ε_E is less than unity.

Figure 14 (conf.1-4) unveils that a turboshaft fed with kerosene is a logical choice for the propulsion of a helicopter, while a diesel-system emerges as a good alternative for the Avgas-piston-engine configuration, but likely also for the low-power turboshaft niche which has a 25% lower $\varrho_{P,m}$ than the one indicated in Table 5. Interestingly, a combination of liquid hydrogen and a turboshaft, appears to offer the lowest m_{prop}. However, the increased fuel tank weight and volume has not been taken into account. This problem will be studied in paragraph 3.3 and will be shown to result in a noticeable rise of the helicopter Gross Weight.

Considering the more-electric configurations 5-8, m_{prop} turns out to be much larger and thus less attractive for helicopter propulsion (Fig.15). However, for the longer endurances, a PEM fuel cell might become interesting, but again, one must be careful with the interpretation of the results as liquid hydrogen has a significant impact on tank weight and volume, and thus also on helicopter Gross Weight.
The effects of T_{ce} are again clearly visible for LiS and AEROPAK™ energy carriers via the slope discontinuity, while the difference in m_{prop} using a SR- or a PM-synchronous motor remains minimum.
The best choice between a SR- or PM-synchronous motor for aeronautical applications remains rather unclear. While [38] concluded the SR-motor to be the best choice for implementation in aircraft due to its robustness and fault tolerance with respect to other electrical motors amongst which the PM-motor, [60] objected against the mediocre volume-weighed power density of the SR-motor and advocated the use of a PM-motor, since it stresses less the bearings in case of a fault leading to radial imbalance forces. According

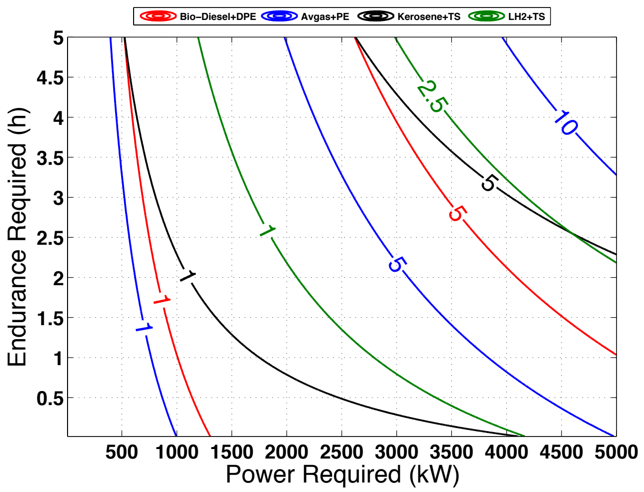


FIGURE 14 : Contours represent m_{prop} (mt)

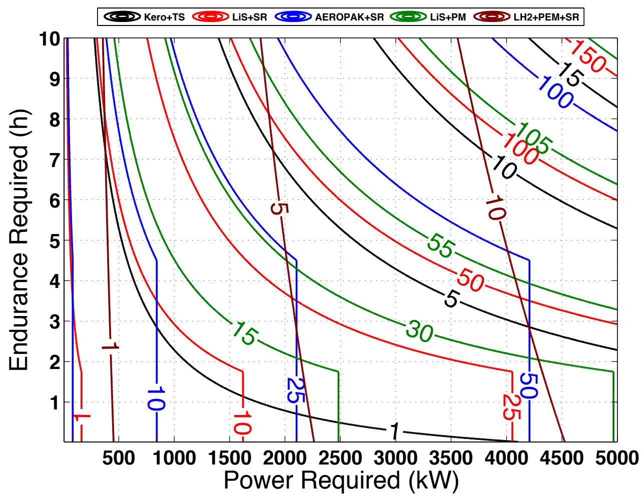


FIGURE 15 : Contours represent m_{prop} (mt)

TABLE 6 : Examined Carrier-Conversion-Element configurations

1	Kerosene + Turboshaft (TS)
2	Avgas 100LL + Piston Engine (PE)
3	Bio-Diesel + Diesel Piston Engine (DPE)
4	LH_2 + Turboshaft (TS)
5	LiS + Switched Reluctance motor (SR)
6	AEROPAK™ + Switched Reluctance motor (SR)
7	LiS + Permanent Magnet motor (PM)
8	LH2 + PEM fuel cell + Switched Reluctance motor (SR)

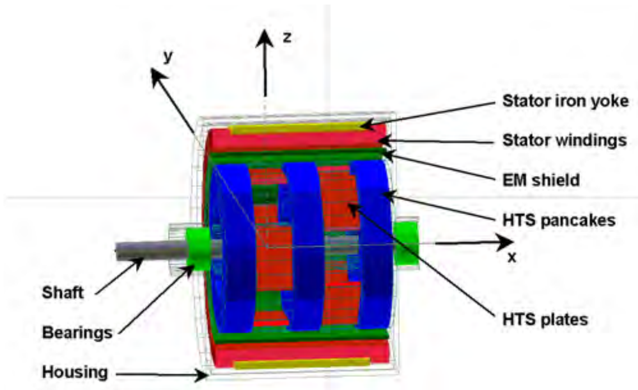


FIGURE 16 : HTS-motor using flux-trapping Courtesy of Masson et al.

to [61], the bearings are the weakest components in electric motors, causing 51% of malfunctions in industrial machines and up to 95% in military applications. [61] suggests introducing multiple phases in order to increase MTBF. Indeed, according to [62], better redundancy levels can be achieved for a system when redundant sub-systems are installed instead of doubling the system. But [63] solved the problems suspending the rotor of the SR-motor magnetically, making bearings obsolete and thus improving MTBF. Therefore the SR-motor was retained for future configurations.

3.2.4 High Temperature Superconductive devices. The introduction of high temperature superconductive materials such as BSCCO (Bismuth-Strontium-Calcium-Copper-Oxide) and YBCO (Yttrium-Barium-Copper-Oxide), having a *critical temperature* T_c[1] near 100K, opened doors to achieve high mass- and volume-weighed power densities for electric motors and generators (Table 5 & Fig.17-20). The impact of HTS-materials on the power generating market is regarded as substantial : [64] predicts that the technology will be implemented in 75% of the motor and 80% of the transformer market, while [65] unveils the cost of HTS-materials to become five times lower than copper.

The importance of the HTS-materials can again be emphasised knowing that Siemens [66] and General Electric [67] investigate the integration of HTS-technologies in their motors and generators, while it is already installed in some ship propulsion systems [68]. [69] examined the implementation of HTS-technology in a Cessna 172 giving encouraging results, while USAF developed and tested a multimegawatt electric power system using HTS-technologies [67]. Therefore, it would be interesting

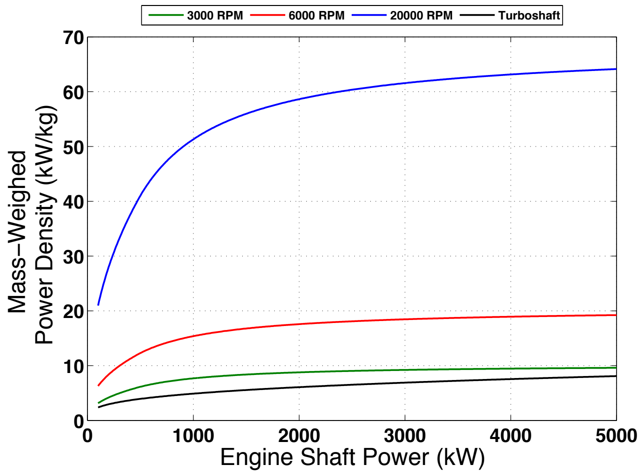


FIGURE 17 : HTS-motor $\varrho_{P,m}$ (20K)

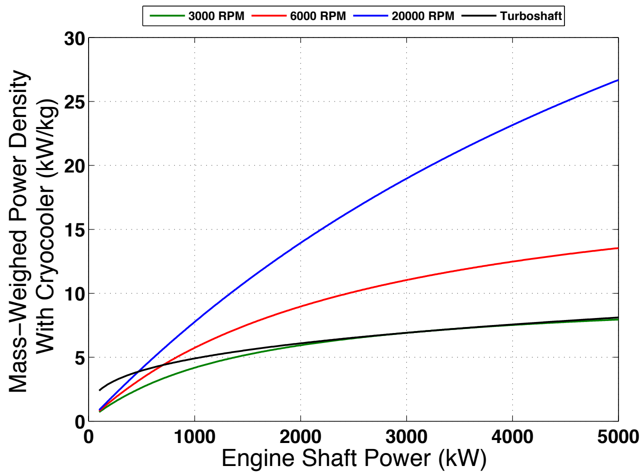


FIGURE 19 : HTS-motor with cryocooler $\varrho_{P,m}$ (20K)

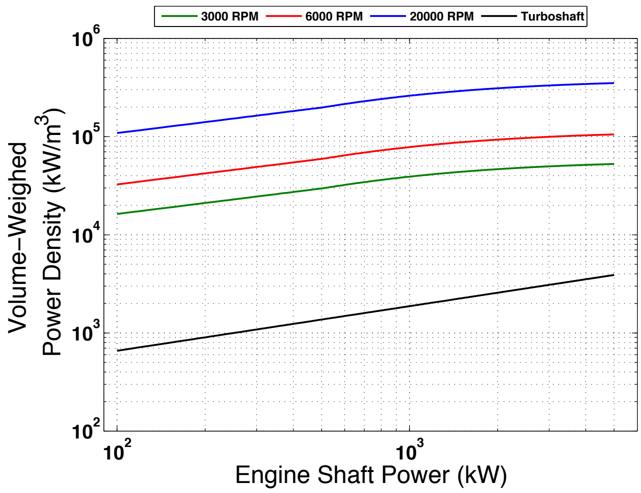


FIGURE 18 : HTS-motor $\varrho_{P,V}$ (20K)

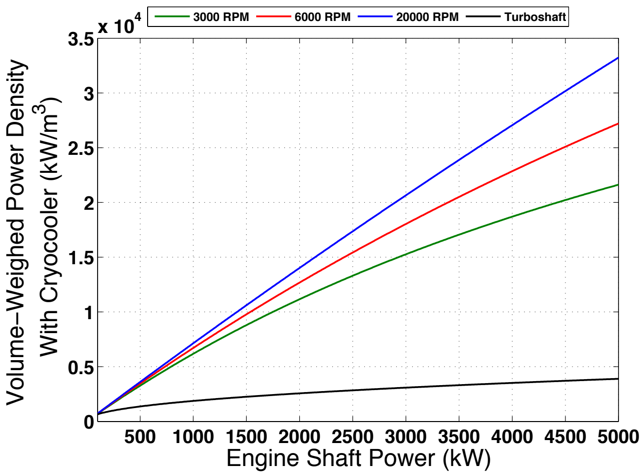


FIGURE 20 : HTS-motor with cryocooler $\varrho_{P,V}$ (20K)

[1] Above this temperature, the HTS-material looses its superconductive characteristics.

to examine in which extent the helicopter could profit from this technology too.

HTS devices achieve their high performance thanks to the high magnetic field produced in the superconductive field windings. Various architectures exist, some use the homopolar configuration [70], others are more exotic using flux trapping [71] (Fig.16), a technique that specifically uses the diamagnetic characteristic of superconductive materials [72].

Two ways are proposed to cool the HTS-materials : via a cryocooler or via LH_2 stored in the helicopter fuel tanks. Then, the mass- and volume-weighed power densities follow in Figures 17-20, using data of [69][73][74]. For the higher range of rotational speeds, the HTS motor performs better than state of the art turboshafts. Though, it is not worthwhile to drive the main rotor with a HTS-motor directly, since the main rotor turns at rotational velocities of one order of magnitude lower than 3000 RPM, which would lower the mass-weighed power density with one order of magnitude, while still needing to be fed electrically with e.g. a high-speed HTS-generator[2] driven by e.g. a turboshaft, but the mass-weighed power density advantage of a mechanical gearbox makes this configuration unattractive [22].
The selection of 6000 RPM and 20000 RPM on Figures 17-20 comes from the typical output shaft speeds of turboshaft engines. The HTS-motor operates at 20K.

3.3 Adaptiveness assessment

Until now, one examined several energy carriers with energy conversion elements and their performance. A turboshaft turning on kerosene showed to be the most obvious combination to produce mechanical power to drive the rotors. However, as seen before, this configuration in combination with the transmission system causes an increase in cost and rises concerns about safety. Seven configurations are evaluated, examining the benefits of introducing liquid hydrogen and more-electric devices in a helicopter (Table 7 & Fig.22). The more-electric devices aim specifically at removing a part of the transmission system, viz. the tail boom shaft with dampers and bearings, and the tail gearbox. The tail rotor will be directly driven by an electric motor.

The modelling of the new technologies follows the following philosophy. First, a *crew and passenger count* N_{cp} is selected, from which the Gross Weight $W_{g,ini}$ can be derived, using a correlation established from a survey done by one of the authors :

$$W_{g,ini} = 6.0461 N_{cp}^2 + 300.18 N_{cp} \qquad \text{[kg] (17)}$$

The impact of the new technologies on the helicopter takes place via a change in Empty Weight W_E and Useful Load UL :

$$dW_g = dW_E + dUL \qquad (18)$$

E.g. the use of liquid hydrogen will cause an increase in fuel tank mass thus W_E, while reducing UL since it has a much larger energy density than kerosene. Here, it is important to define a reference energy quantity carried aboard. Indeed, considering the *maximum endurance* E_{nd} as performance parameter, a lighter helicopter will require less fuel for a given N_{cp}. Hence, one introduces a second independent variable, F_E, the *stored energy fraction* :

$$F_E = \frac{E_{fuel}}{E_{fuel,W_{g,ini}}} \qquad \text{[-] (19)}$$

where $E_{fuel,Wg,ini}$, the *carried reference energy* at $W_{g,ini}$ and E_{fuel}, the *internally stored energy* in the helicopter.

Note that the WER of [6] for the weight groups in Table 1 all depend on W_g. The model uses these WER, but the implementation of new technologies does not affect all weight groups. It is assumed to be the case for weight groups 9, 10, 14 and 15. As a matter of fact, the instruments and avionics weight will more depend on range, and cabin amenities on N_{cp}. In the model, their mass was obtained via $W_{g,ini}$, F_E and N_{cp}.

The body-weight group 4 deserves some additional attention. According to [6], the mass of the helicopter structure depends on its wetted surface. The wetted

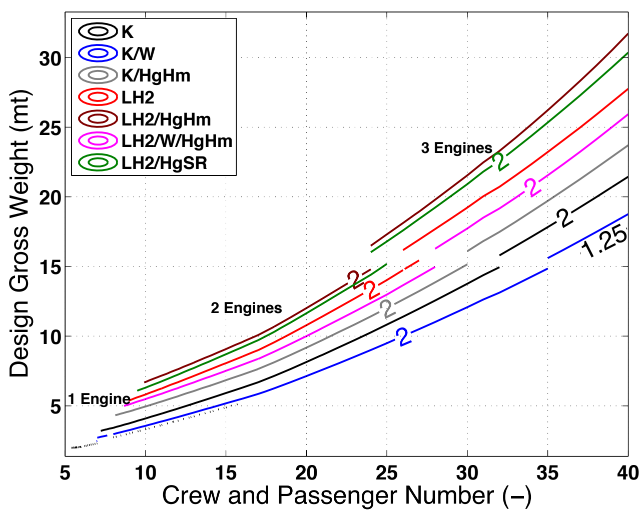


FIGURE 21 : Configuration evaluation, 2h endurance (See Table 7)

[2] A HTS-generator has already been developed and tested successfully for the USAF [67].

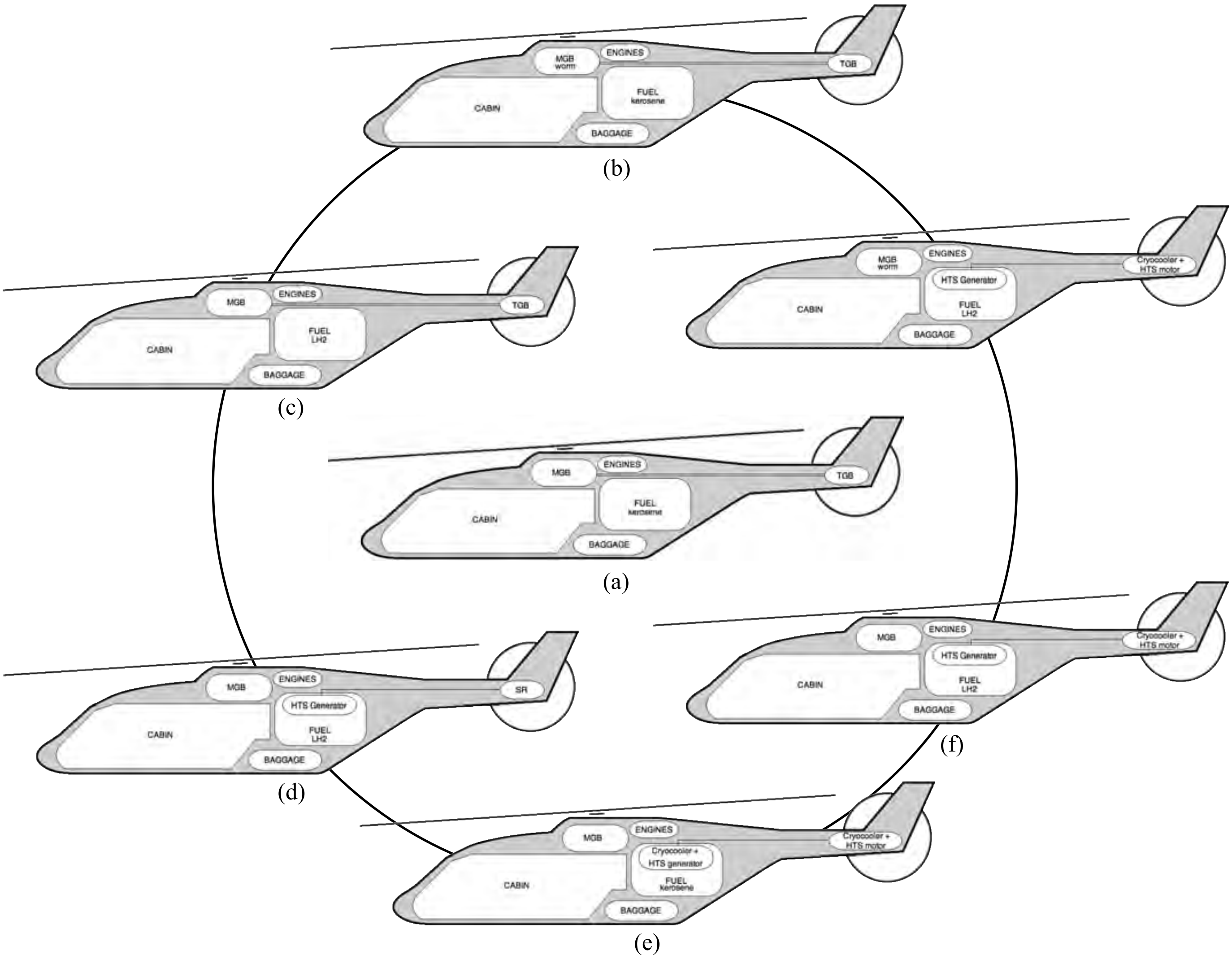


FIGURE 22 : The examined configurations

TABLE 7 : Configuration overview

Nr.	Fuel	Worm gearing	TR driver	HTS generator	Abbrev. Fig.21
(a)	Kerosene	no	Turboshaft	no	K
(b)	Kerosene	yes	Turboshaft	no	K/W
(c)	LH_2	no	Turboshaft	no	LH2
(d)	LH_2	no	SR	yes	LH2/HgSR
(e)	Kerosene	no	HTS motor + CrC	yes +CrC	K/HgHm
(f)	LH_2	no	HTS motor + CrC	yes	LH2/HgHm
(g)	LH_2	yes	HTS motor + CrC	yes	LH2/W/HgHm

CrC = Cryocooler installed

surface encapsulates a certain volume. It is therefore sensible to relate the body mass to a *Useful Volume* V_{use} :

$$V_{use} = V_{MGB} + V_{Eng} + V_{ft} + V_{cab} + V_{lug} \quad (20)$$

where V_{MGB}, V_{Eng}, V_{ft}, V_{cab} and V_{lug} are respectively the volume of the main gearbox, the engines, the fuel tank, the cabin and the luggage compartment. For these volumes, correlations were established and implemented in the model.

Finally, for UL :

$$UL = N_{cp}m_p + m_{pay} + m_{fuel} \quad (21)$$

where m_p represents the mass of one person, equal to 77kg as indicated by EASA CS-27/29, m_{pay} the payload mass and m_{fuel} the fuel mass added to the helicopter such that the maximum Gross Weight is obtained. m_{pay} is nonzero if the fuel tank with volume V_{ft} is completely filled and additional mass needs to be added to obtain W_g.

Now, a parametric study is possible for the configurations shown in Table 7(a)-(g). The results are obtained iteratively. A rather simplistic representation of the calculation process is as follows :

$$W_g^{++} = W_{g,ini} + \Delta W_E(W_g^{+}) + \Delta UL(F_E) \qquad (22)$$

Figure 21 shows the results for an arbitrarily chosen endurance of 2 hours. Configuration (a) serves as the benchmark. It appears that a lighter mechanical transmission system such as the worm gearing allows an improved performance (b), while the more-electric solutions all cause a Gross Weight increase for a fixed N_{cp}. Also, there are multiple solutions possible for a given N_{cp}. This result originates from the fact that an increase in F_E introduces an increase in W_g, needing more power to be installed, consequently needing an additional engine, thus leading to an increase in engine SFC (lower power category engine), again raising W_g, and eventually ending in an unchanged endurance. In short, when more fuel is installed, more fuel will need to be burnt to airlift the heavier and less efficient helicopter.

Interestingly, the helicopter configuration (e) using a HTS-motor to drive the tail rotor and fed by a HTS-generator, while both refrigerated with cryocoolers at 20K, proves to be the second best solution.

Liquid hydrogen as a fuel carrier (c), in contrast with what one expected earlier in Figure 13, raises Gross Weight over 50% for the smaller helicopters, to 25% when it concerns the larger ones. This is explained by the significant weight impact of the fuel tank and the increase of structural weight required to store the low-density liquid hydrogen.

Comparing (d) and (f), the HTS-motor with cryocooler performs less than the configuration with SR-motor. Probably, this results from an over-estimation of the mass-weighed power density for the SR-motor, wherefrom one value was known at 15000 RPM (Table 5). Obviously, the tail rotor does not turn at this speed, which was accounted for in the HTS-motor calculations. Since a higher torque will be necessary, the SR-motor will be heavier. The introduction of worm gearing (g) reduces the Gross Weight and thus required tail rotor power, eventually leading to a smaller electric motor and a significant drop in mass.

An important notice is the need for a HTS-generator when driving an electric motor, for the calculations assumed to be operating at 10000 RPM. Indeed, conventional generators are bulky and heavy and would drive the helicopter Gross Weight beyond acceptable limits. However, a major drawback of the HTS-devices is the cooling time [75]. A fast and safe cooling method should need to be sought for in order to enhance the helicopter's operability.

4. Conclusions

This work evaluated the adaptiveness of a conventional helicopter for more-electric and alternative transmission systems. The following can be deduced :

- A cost, safety and performance assessment of the conventional helicopter we know today has unveiled the powerplant and drive subsystems to be of major concern.
- More-electric technologies promise to be more reliable and therefore some electric systems were investigated for their suitability in a helicopter environment.
- Magnetic gearboxes have inherent safety characteristics, but were too heavy to be installed in a helicopter. Though, the cycloid permanent magnet gearbox appears attractive if weight and reduction ratios could be improved.
- Other energy carriers were evaluated in order to verify the helicopter's adaptiveness for more environment friendly solutions, but only kerosene, bio-diesel and hydrogen exhibited sufficient energy levels. Batteries and fuel cells are currently not performing enough to achieve the required performance levels.
- The use of a High-Temperature-Superconductive motor/generator appeared possible and especially attractive when a free cold source such as liquid hydrogen is available. Though, the heavy tank weight and large volume to store liquid hydrogen raises the helicopter Gross Weight, requiring more fuel and power to achieve the same performance.
- The use of kerosene-driven turboshafts, driving a cryocooled HTS-generator, which in turn feeds a HTS-motor with crycooler serving to drive the tail rotor should deserve attention since a relatively limited increase in Gross Weight was observed.

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