THE HYBRID HELICOPTER DRIVE – A STEP TO NEW HORIZONS OF EFFICIENCY AND FLEXIBILITY

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Summary

As all other industrial systems, also helicopters will have to contribute to fuel saving and mitigation of the anthropogenic climate changes. One response to this challenge could be the use of hybrid drives consisting of modern turbo-charged Diesel engines, generators and electrical motors for main and tail rotor. The Diesel engines must be subdivided into several smaller units, which can be suitably placed in and/or on the fuselage. This is possible only due to the separation of energy production and rotor drives. The significantly lower fuel burn of Diesel engines is compensating to a great part mass surplus and transformation losses.

Besides further advantages typical for Diesel engines, such as low maintenance efforts and good performance at hot and high conditions, effects specific to hybridisation, such as the unproblematic variations of the rotational speed are of importance. So, today's helicopters, driven by turbo or piston engines are designed to limited rotor rpm variations only, mainly due to the operational engine characteristics/efficiencies. Hereby, they have no access to the available operational flexibility potential, which allows adapting the rotor rpm to the actual flight condition. In addition, these systems suffer from architectural inflexibility by configurational constraints with respect to integration and potential changes of main gearbox and engines. These components have to remain close to the rotor position and require high development and integration efforts in case of larger system changes requested, e. g. by upgrades of the respective helicopter type.

The paper describes a new possibility to overcome the above-named disadvantages by applying hybrid drive technology. It illustrates the related basic concept, consisting of a separate power pack with combustion/electric power supply systems and advanced direct drive electric motors for main and tail rotor.

The actual state of the art of hybrid drive technology is elaborated, including available system components and their typical power densities. A comparative mass and performance balance for conventional and hybrid systems illustrates the feasibility of the latter technology.

To show the compatibility of the hybrid drive technology with a generic helicopter design and to depict the related architectural flexibility, some integration alternatives for a helicopter of the EC135 class are discussed.

The paper describes the operational advantages attained by significant rotor rpm variations and mild rotor shaft tilting. They are made possible by the specific features of the hybrid drive system and allow on one hand to reduce required power as well as noise radiation during cruise and on the other hand to provide sufficient performance during manoeuvres, hover and climb. The respective influence on the power requirement is discussed with the aid of a modified simple energy balance model based on predictions by a comprehensive flight mechanics code.

Abbreviations:

ICE	Internal combustion engine
MGB	Main gear box
MR	Main rotor
OEI	One engine inoperative
rpm	Rotations per minute
TFM	Trans-Flux-Disk motor
TR	Tail rotor

1 INTRODUCTION

The general challenge to save fuel due to the decline of the worldwide oil reserves and the anthropogenic climate changes has a heavy impact also on helicopters. These are commonly driven by turbines, some smaller ones also by Diesel engines.

With respect to fuel consumption, the latter ones are superior to turbines for longer distances, where their higher weight is compensated by their lower fuel burn. For larger helicopters, a drive system consisting of Diesel engine(s) and gear box may become however too bulky and difficult to integrate, especially on the cabin roof.

Therefore, in the helicopter community, considerations on possible alternatives have started. So, Sikorsky has just announced the near first flight of a fully electrically driven helicopter UAV, Ref. 1.

Certainly, such systems represent the future needs even if adequate sources of electric energy, such as fuel cells of the required energy content are not yet in sight. Therefore, hybrid solutions can be a realistic intermediate step.

They are characterised by a mixture of chemical and electrical energy. Different levels of hybridisation are possible: A mild hybridisations may boost the rotor by an additional electrical motor to cope with extreme flight conditions. It won't be further considered in this paper.

A full hybridisation uses the combustion motors (ICE) only as energy generators. They provide electrical energy by generators which power electric direct drive motors for main and tail rotor.

The different scenarios are summarised in Table 1 in form of four alternatives. The titles describe the path along which the torque is transmitted from the energy source to the rotors.

Since turbines are lightweight and largely today's standard engines, they could be used also for a full hybridisation. In this case, one has to renounce on the compensation of a great part of the weight of the added components generator, electronic control and electrical motors, by the lower fuel burn of turbocharged Diesel motors. Especially this beneficial effect appears desirable, since the added parts are obviously heavier than removed gearbox and tail rotor drive train.

No	Path of mech./elect. energy to the rotors
1	**Turbine → MGB → MR / TR**
	a) light engine, high fuel burn, b) low transformation losses, c) MR rpm variation impacting ICE efficiency, d) low design flexibility due to rigid MGB/ICE link e) family concept limited by MGB
2	**Diesel engine → MGB → MR / TR**
	a) heavier engine, lower fuel burn, b) – e) as alternative 1 h) For larger HC: bulky ICE system on cabin roof, difficult to integrate
3	**Turbine→ Generator → E-motor → MR/TR**
	a) light engine, high fuel burn, b) high transformation losses c) MR rpm variation not impacting ICE efficiency d) High design flexibility e) Family concept eased by MGB disappearance f) Mild rotor shaft tilting according to flight condition possible g) Power boosting by battery possible
4	**Diesel→ Generator → E-motor → MR/TR**
	a) heavier engine, lower fuel burn, b) – g) as alternative 3

Table 1 Spectrum of possible and realistic combinations (1 to 4) of drive system components and their pros and cons (a to h)

As a result of the comparison in Table 1, alternative 4 may be considered as optimum solution under the following prerequisites:

- The use of modern turbo-charged Diesel engines, especially if the power / weight ratio will be increased further in the next years,

- A splitting up of the Diesel engines into several smaller units, which can be suitably placed in the fuselage - possible only due to the separation of energy production and rotor drives,

- The application of newly developed lightweight and flat Trans Flux E-motors - TFM (see chapter 4.3 and Figure 10)

At first glance, one may oppose that Diesel engines are heavier than turbines. However, the significantly lower fuel burn is helping to make the solution appear attractive. For specific missions, such as rescue or law enforcement, this holds true also for short mission times, since due to unforeseeable events, considerable fuel has to be carried by the helicopter as reserve. Further advantages typical for Diesel engines are low maintenance efforts and good performance at hot and high conditions – both significant advantages over turbine engines.

In addition, as explained in Table 1, unproblematic variations of the rotational speed, higher design flexibility, easier realisation of upgrading and family concepts, as well as more favourable weight distributions are assets of the full hybrid approach. This will be described further in the following.

2 MOTIVATION

As mentioned above, alternative 4 from Table 1 is capitalising first on the typical Diesel pros: The relative low fuel burn is supported by low maintenance costs due to the long experiences in this area. The charging of the motor makes it superior to the turbine for hot and high conditions, where the turbine performance is drastically dropping, requiring a high over-sizing. A second advantage consists of a number of positive aspects stemming from the separation of energy production and rotor drives, described in the following.

2.1 Variation of rpm

Large variation of the rotational rotor speed – unproblematic for electric motors - can significantly enhance the rotor performance (see chapter 8). For low rotor loading, a lower rpm reduces required power and fuel burn. For the tail rotor, this can be extended during cruise even up to a full stop, yielding a strong drag reduction. Yaw control may be accomplished in this case by a rudder of the vertical stabiliser.

On the contrary, an rpm increase will support both high g turns by increased thrust capability and high speed flight by providing higher dynamic pressure on the retreating blade. Finally, close to noise sensitive areas, the rotor sound emission can be strongly reduced by lowering the blade tip speed.

For today's helicopters, this beneficial potential is accessible only to a small extent. The main reason is the rpm dependant efficiency of combustion motors, especially turbo engines, and the torque limits of the main gearbox. In contrast, an energy generator, mechanically separated from the rotor drives can mostly run in its sweet point (i. e. at its greatest efficiency).

To manage this, from the total number of ICE only as many units are running as required. The others are shut off or running in idle conditions. Figure 1 illustrates the minimisation of fuel burn by the successive operation of up to four Diesel engines, 200 kW each. The power demand is satisfied by starting with one engine, followed by running up an additional motor always if the next 200 kW step is reached. This procedure allows to attain as soon as possible low specific fuel consumption values and to stay close to them. A decrease in required power is managed by proceeding in the opposite direction.

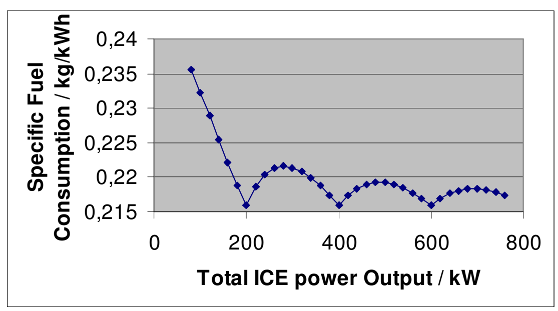

Figure 1 Specific fuel consumption for successive operation of up to four Diesel engines

Because of potential engine failures, single engine helicopters suffer from operation constraints. These are overcome by twin engine helicopters, but with the constraint of a certain overpowering to allow a flight continuation after engine failure.

With the increase of the number of combustion engines beyond two, the degree of redundancy to be held available is decreasing. Triple engine turbine driven helicopters are known only for heavier weights. Obviously, three engines add a too high complexity to smaller helicopters. On the contrary, Diesel-driven helicopters above the lower weight category may always need a partitioning to avoid too bulky configurations. This holds true also for hybrids.

So, a triple engine hybrid helicopter of the EC135 class according to Figure 2, bottom, would require 6% lower installed power (690 kW vs. 736 kW). Note that higher hybrid transmission losses of 7% compared to the turbine are taken into account in the figure.

In addition, under OEI conditions, the triple engine drive of Figure 2 would dispose on 460 kW, compared to 368 kW for the twin engine drive for maximum continuous power. This would increase even to 517 kW in case of four engines.

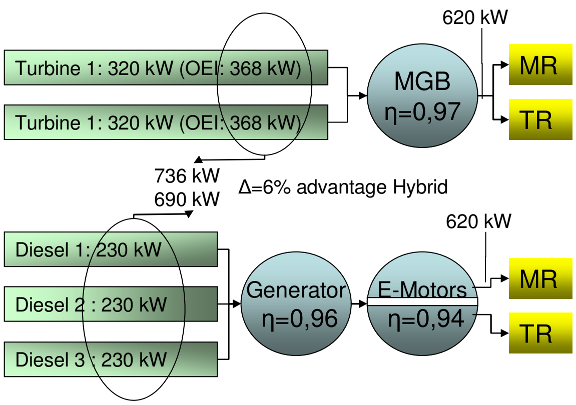

Figure 2 Required installed power for turbine and hybrid drive

In addition to the aforementioned overpowering, turbines are designed to stand a short but considerable overstraining (for 30 seconds or 2 minutes respectively). Hybrid drives don't need this capability but rely in such cases on a battery-supported boost of the rotor drives.

2.2 Design Degrees of Freedom

By removing the main gear box and hereby the rigid mechanical coupling between energy generator and rotor, a much higher design flexibility is attained. It allows to place the hybrid components in a convenient way to guarantee optimum cabin utilisation and centre of gravity range. Figure 3 illustrates as one possible alternative a motor assembly below the cabin floor. It shows also the flat shape of the new direct drive Transverse Flux electro-motor (TFM), just under development. In the past, size and weight of high torque electro-motors impeded their application on the helicopter.

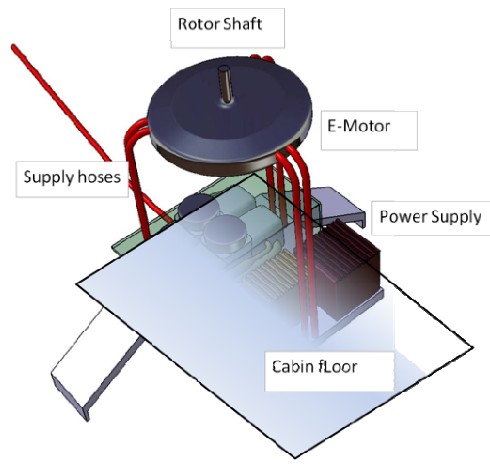

Figure 3 Integration of hybrid system

The separation of energy generation and rotor drive allows also for an easier upgrading of a helicopter towards higher take-off weights and larger rotor diameters. Especially the latter effect is often requiring a new main gear box development and therefore a severe development obstacle.

The ability to create a helicopter family concept is strongly supported by the serial structure of the hybrid design, i. e. by several identical rotors in E-motors and generators as well as by several identical combustion engines. So, a larger version may emerge e. g. by enlarging the number of those elements.

The opportunity to shift heavy masses, such as gear box and turbines, from above the cabin roof to the bottom allows for higher stability during autorotation and slope landings, lower fuselage strength requirements and higher passenger crash safety.

By removing the main gear box above the passenger heads, also strong comfort deficits can be defeated caused by annoying discrete tones produced by tooth intermeshing forces.

3 GENERAL SYSTEM DESCRIPTION

The proposal for a hybrid helicopter drive is based on the use of combustion motors, preferably compact turbo-charged OPOC, Wankel or Zoche engines, coupled with generators. A possible configuration is given in Figure 4. The produced electric power is transferred to main and tail rotor, equipped with electric motors. A potential surplus of electric energy can be stored in a battery, which on its part will be used to boost the rotor in acceleration and emergency cases.

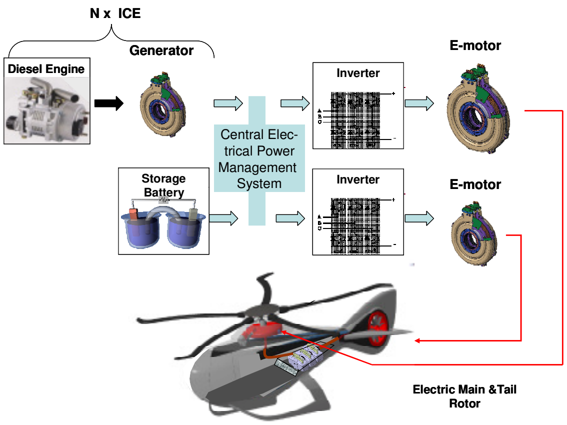

Figure 4 Full hybrid system structure

The installation of the combustion engines below cabin floor, mentioned in chapter 2.2 is illustrated in Figure 5. Main and tail rotor drives are realised by disc-shaped electrical Trans Flux Motors (see chapter 4.1).

The main rotor drive in Figure 5 is suspended in a way to allow main rotor tilting to reduce fuselage drag and shaft moment (see also chapter 5).

Figure 5 Integration of the E-motors for main and tail rotor

4 POWER PACK AND ROTOR DRIVE

The power pack unit consists of turbo-charged Diesel motor, generator, batteries, inverters and central power management system (see Figure 4).

4.1 The Combustion Motors

Because of their low fuel burn characteristics, only Diesel motors are considered. Available Diesel motors of high power density are depicted in Table 2.

Automotive Diesel	1,0 kW/kg max
MB 6 Cylinder OM642	0.9 kW/kg
Diesel V8 Mecachrome	1.7 kW/kg (incl. cooling)
Alternative Concepts	
OPOC Opposed Piston EM100	1.5 – 2 kW/kg
Zoche Aero Diesel	1 – 2,1 kW/kg
Wankel (SUPERTEC - KKM353)	2,8 kW/kg

Table 2 Available Diesel Motors of high power density

A recent OPOC development, the EM100 is illustrated in Figure 6 showing the four opposed pistons. It is expected to supply 220 kW at a weight of 105 kg. Figure 5 and Figure 13 illustrate a configuration with three EM100 below cabin floor, while Figure 14 depicts an upper arrangement.

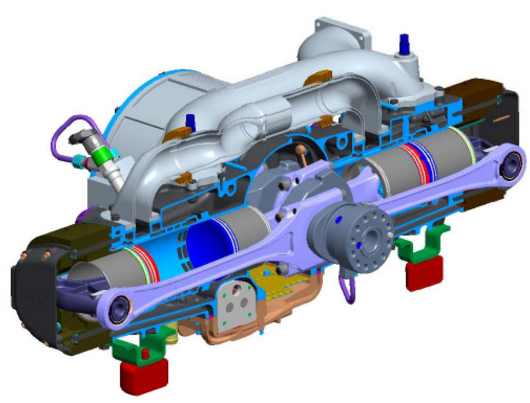

Figure 6 Turbo-charged OPOC EM100

Figure 7 illustrates a turbocharged Wankel Diesel motor of WANKEL SUPERTEC. Six units of the type KKM353 would supply 630 kW at a weight of about 220 kg. A possible installation is proposed in Figure 15.

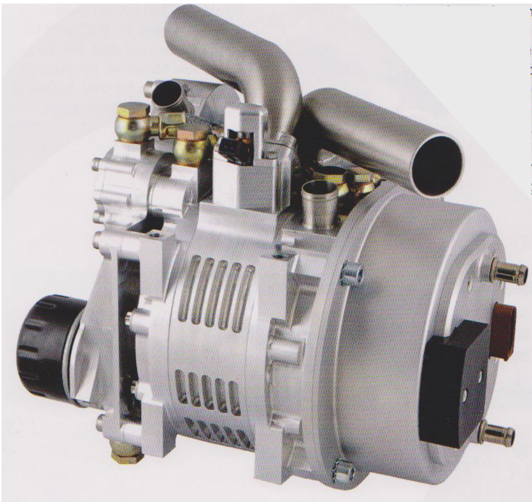

Figure 7 Turbocharged Wankel

Figure 8 shows the turbo-charged, inter-cooled Zoche Diesel motor ZO 02A. It supplies 220 kW at a weight of 123 kg. In contrast to OPOC and Wankel it is air cooled. It could be installed similarly to the OPOC EM100.

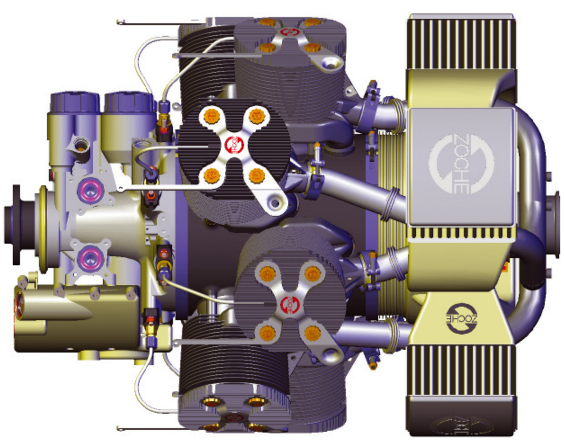

Figure 8 Zoche Diesel ZO 02A

The challenges of the new Diesel motors will be to prove/improve efficiency, endurance and low maintenance efforts.

4.2 The Batteries

Two available batteries of required power density are shown in Table 3

State-of-the-art Li-Ion	100 Wh/kg, 2 kW/kg
LiS; SionPower	400 Wh/kg, 2 kW/kg

Table 3 Battery performance

A LiS battery of 100 kg weight provides 40 kWh and 200 kW. This would correspond to a 12 minutes battery-supported 200 kW boost.

4.3 E-Motors and Generators

The ultimate key to realise full hybrid helicopters are lightweight electric generators and motors for main and tail rotor. Up to the present however, there are no direct drives available on the market with the specified performance, complying e. g. with the weight requirements for a helicopter of the EC135 class. This would mean 600kW for the main and 230kW for the tail rotor. The actually available e-motors are displayed w.r.t. their power density in Figure 9.

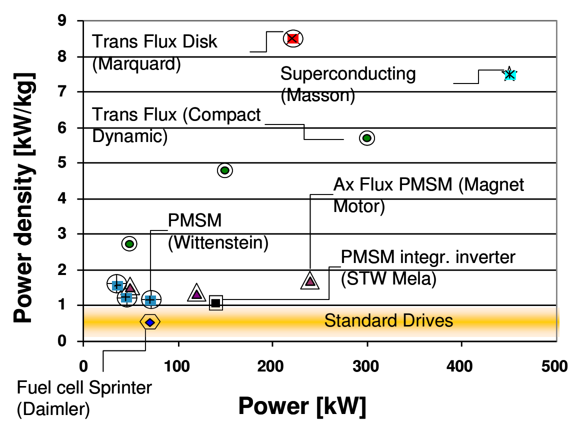

Figure 9 Power density of electrical machines

The most promising approaches are Trans-Flux-Disk-Motors (TFM - Figure 10). The TFM was first introduced and named by Weh in 1986 (Ref. 4). Since the TFM allows the pole number to be increased without reducing the magneto-motive force per pole, it is capable of producing power densities much higher than conventional machines.

In a TFM the electromagnetic force vector is perpendicular to the magnetic flux lines.

It is common knowledge that an air gap propulsion force $f_x = 60\frac{kN}{m^2}$ can easily be achieved by use of actively cooled tubular copper conductors. This force result into a torque of

$$T_1 = \frac{\pi \cdot D_{St}^2 \cdot b_{St} \cdot f_x}{2}$$

per single rotor disk of a TFM.

In an exemplary design of the crucial main rotor drive we assume the following data:

Rotor disk diameter	$D_R = 1.35\,m$
Mean stator diameter	$D_{St} = 1.26\,m$
Stator width	$b_{St} = 0.06\,m$

This geometry results into a torque of 9 kNm per rotor disk of the TFM.

A particularly lightweight TFM version is expected from a new design with composite shells and integrated inverter of the University of the German Federal Armed Forces by R. Marquard (Figure 10 - no Ref. yet), which has just started its first prototype open-circuit tests. For the helicopter main rotor, this concept shall comprise two disks achieving a total torque of 18 kNm at a mass near 150 kg.

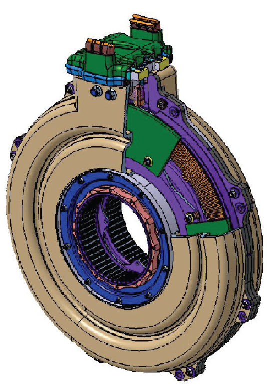

Figure 10 New TFM design for rotor drive

The tail rotor may be driven by a TFM in the hub, or, as shown in Figure 5, as a torus around the Fenestron opening, the blade tips being fixed to its rotating component. The weight is assessed to be about 20 kg. Both motors will be arranged in the fuselage according to Figure 5.

Redundancy is achieved by strictly separating the individual phase groups of the multiphase motor electrically, magnetically and thermally. Thus, with one phase group failing the drives are still providing torque - with reduced performance. Also the integrated inverters feature multiple redundancy.

The generators are of the same type as the E-motors. Since they are running with much higher rpm than the latter ones, weight and size are significantly lower.

The challenges of the new electric systems will be:

- To achieve targeted efficiency and mass,
- To assure the reliability and
- To control inherent EMC effects.

5 SPECIFIC CONFIGURATIONS FOR ENHANCED FLIGHT-PHYSICAL EFFICIENCY

The lack of a rigid connection between rotor drive and helicopter fuselage allows tilting the rotor shaft together with the electric motor in flight direction of a fast forward flying helicopter. Hereby the usual strong drag increase by the high negative fuselage attitude is avoided. For this purpose, the electrical drive is suspended tiltable on the fuselage roof (see Figure 11 and Figure 5).

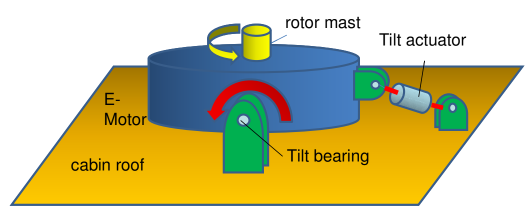

Figure 11 Tilting mechanism of main rotor drive

The tilting angle goes up to about 15 degrees nose down. The fuselage attitude of lowest drag will be controlled by elevators. Such a fuselage control would lead without rotor tilting to significant blade root bending moments and intolerable shaft moments.

In order to reduce the vibratory loads transferred from the rotor to the electric drive and the cabin, tilting actuator and bearing can be designed as active components of high dynamic bandwidth. They will excite defined vibration modes of the electric motor, able to generate out-of-phase oscillations and to extinct hereby the existing ones

In addition, the vibratory rotor loads can be defeated by an active control through small servo flaps integrated into the trailing edge of the rotor blades (see Figure 12 and Ref. 2). These also generate out of phase vibratory loads on the rotor blades suppressing the original ones stemming from rotor / flow interaction. In contrast to the active technology at the e-motor suspension, the active flaps are counteracting the vibration excitation directly at its source, which represents the most efficient way.

Both active mechanisms, the e-motor suspension and the flaps are working at a frequency f_K composed by rotational frequency Ω multiplied by blade number b and by an integer multiple factor n.

$$\mathbf{f_K = \Omega\, b\, n}$$

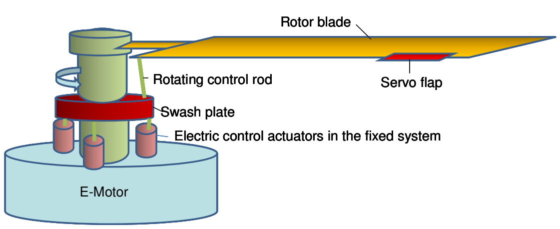

Figure 12 Active Servo flaps

Finally, as a further important step towards the fully electrical helicopter, on the electric drive likewise electric boosters could be installed (see Figure 12), the size of which could be significantly reduced by the flap. This is caused by the servo effect, the flap would effect to the boosters by introducing appropriate 1/revolution torsion moments ($f_k = \Omega$) along the blades' control axes.

6 FIRST DESIGN CONSIDERATIONS OF A HYBRID HELICOPTER

As mentioned in paragraph 2.2, the removal of the rigid coupling between heat-engines and rotor is increasing significantly the degrees of freedom of fuselage design. It could allow e. g. to move the heavy drive train masses of conventional designs to the cabin floor, as shown in Figure 5 and Figure 13. The necessary space is available, since with the fuel burn also the tank volume is drastically reduced compared to a turbine configuration.

In order to maintain a low door sill for pilots and passengers, a configuration of three OPOC or three Zoche Diesel motors would require raising the floor of the rear cabin (Figure 13). This could be avoided by smaller motors such as the Wankel Diesel.

The floor step appears however acceptable, since the disappearance of gearbox and turbo-engines will provide additional head clearance. So, the cabin height above the engines in Figure 13 would be for a helicopter of the EC135 class about 1,2 m.

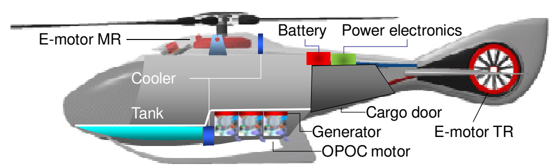

Figure 13 Hybrid configuration with 3 OPOC Diesel motors below Cabin Floor

In order to avoid the raising of the cabin floor and the larger harness weight by a smaller distance between generator and motor, cabin roof installations as shown in Figure 14 and Figure 15 are also possible. Naturally, this detracts from the advantage of the low centre of gravity.

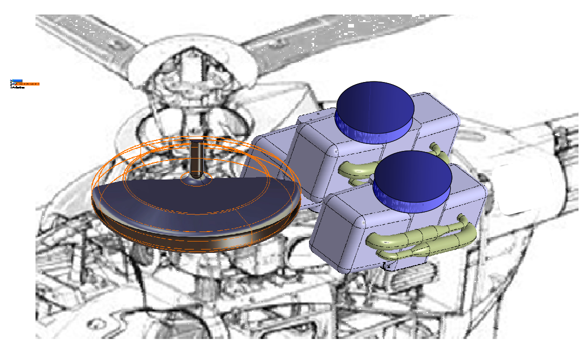

Figure 14 Hybrid configuration with 3 OPOC Diesel motors on cabin roof

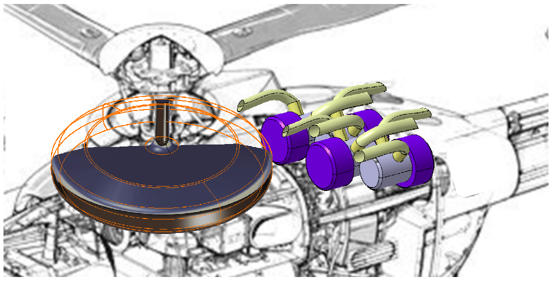

Figure 15 Hybrid configuration with 6 Wankel Diesel KKM353 motors on cabin roof (4 visible)

7 ASSESSMENT MODEL OF REQUIRED POWER

In order to assess power and fuel quantity required for specific missions, a simple energy balance method has been applied (Ref. 3). Figure 16 shows the procedure applied, starting with the mission definition. The energy method predicts the power required for the different mission elements and iterates with the aid of fuel burn curves (Figure 1) the fuel quantity consumed.

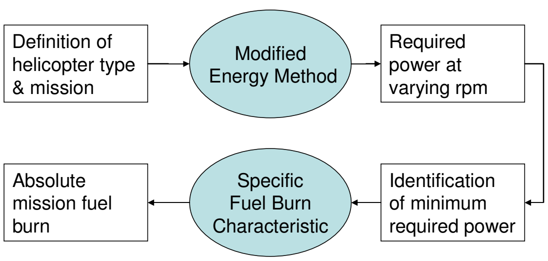

Figure 16 Computation of required power and fuel burn by modified energy method

For comparison, all computations are made both for a turbine and for a hybrid drive. For the latter one, a fuel burn optimisation by rpm variation was made. To allow this, the energy method has been modified by a simple law, based on the blade area weighted thrust coefficient c_T/σ. It allows approximating the effect of stall and compressibility limits encountered by the rpm variations. This law was deduced from results of a comprehensive ECD flight mechanics code (Figure 17).

In order to investigate the opportunity to steadily minimise the required power by rpm variations in a deeper way, further investigations on the matter have been performed by the comprehensive flight mechanics DLR code S4 (Ref. 5).

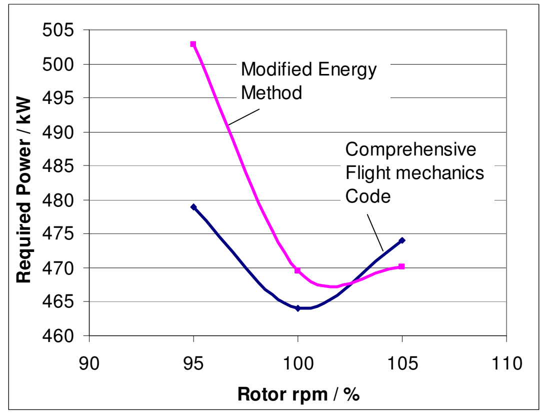

Figure 17 Comparison of required power predictions of a light helicopter calculated by modified energy method and comprehensive code. V=126 kt at 5000 ft ISA, take-off mass ~ 3200 kg

8 PREDICTION OF RPM EFFECT ON REQUIRED POWER

The code S4 yields rotor forces and moments, required power and control angles of main rotors. For the simulation of defined flight conditions, it needs therefore trim values from outside - in this case from the Eurocopter HOST code (Ref. 7).

S4 uses steady and unsteady aerodynamic coefficients, uncoupled blade modes for flap, lag and torsion and prescribed wake geometries following Beddoes (Ref. 6) in forward flight. The limits of possible rpm variations are identified by the steepness of the slope of power demand vs. rpm, the control angles and stall onset signals (peaks) in the blade torsion moment c_m.

As an example of predicted stall onset detection, Figure 19 depicts the related strong blade torsion moment peak during cruise flight with 131 kt near 270°.

In order to verify the code's capability to predict rpm effects on power demand, comparisons with test results of the research programme HART II (Ref. 5) have been made

Within this programme, numerous wind tunnel tests with a Mach-scaled 40% BO105 model have been conducted, amongst others also on the influence of rotor rpm on required power. Figure 18 (by van der Wall, DLR) shows the power demand characteristics vs. shaft angle for different tip Mach numbers – measured and predicted.

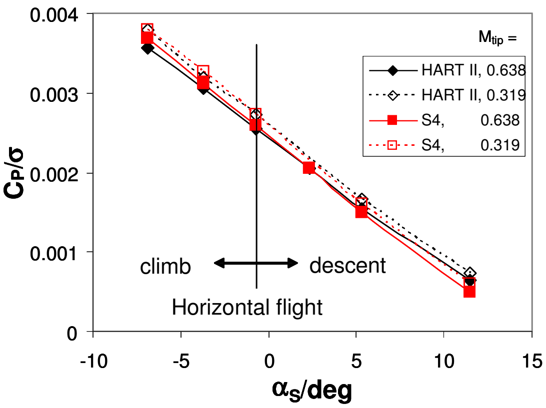

Figure 18 Comparison of analytical (S4) and experimental (HART) results on blade area weighted power coefficient vs. shaft angle

Since the correlation between theory and experiment are convincing and there exist numerous further helpful research results on the BO105, the following investigations have been performed for a BO105 main rotor. In order to avoid undesired Re-number effects, a full-scale configuration has been chosen.

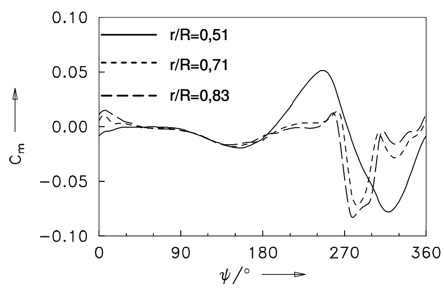

Figure 19 Identification of stall onset by c_m peak during cruise with 131 kt at 5000 ft ISA. Ω/Ω_0=0,8; μ=0,39; c_T/σ=0,13; $M_{Tip90°}$=0,72

The savings of required power for a horizontal flight with 131 kt are depicted in Figure 20. The effects of drag divergence are visible for high rpm, while stall effects at low rpm (Figure 19) are slowing down the desired power drop in this region. Naturally, this behaviour - nearly independent from altitude – is strongly dependant on rotor loading, i. e. the lower the rotor loading, the higher the power demand gains.

According to Figure 20, during cruise with 131 kt, about 10% of the required power can be saved by rpm reduction. For the transition region around 65 kt, similar trends could be shown.

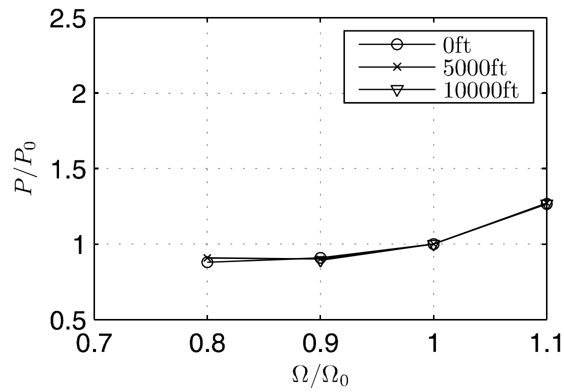

Figure 20 BO105 required power for horizontal flight with 131 kt, take-off mass=2300 kg

By flying turns with increasing load factor n, at about c_T/σ = 0,15, for the configuration considered, the stall limit is reached. In order to stay below it, the rpm can be increased, leading to lower c_T/σ values and therefore higher flyable load factors (see Figure 21). In this case, the new load factor limit is defined by the available rotor power, since the power demand increases strongly with the rpm.

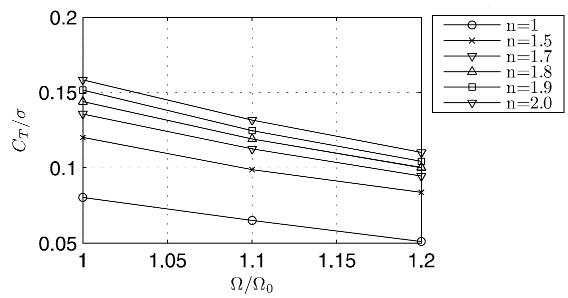

Figure 21 BO105 required power for turns with 65 kt, m=2300 kg, 5000 ft ISA

9 MISSION-DEPENDING REQUIRED POWER

In order to evaluate the feasibility of the hybrid compared to the turbine drive, different mission scenarios have been simulated with the aid of the modified energy method (Figure 16) for a helicopter of the EC135 class. All values shown in the following refer to this class.

The mass balance of turbine vs. hybrid drive - the latter one with 3 turbocharged 220 kW OPOC diesel motors (Figure 6) - is described in Table 4 and Table 5. The difference adds up to about 180 kg.

Turbine Drive *Mechanic components*	Mass / kg
2 turbines. MGB, structural elements, tail rotor drive	443
Electric components	
power box, generator/starter, battery	91
Total	**534**

Table 4 Elements of the turbine drive to be replaced by the hybrid system

Hybrid Drive *Mechanic components*	Mass / kg
3 OPOCS motors, coolers	415
Electric components	
MR-motor, TR motor, power electronics, generators, battery, harness	302
Total	**717**

Table 5 Additional masses of a hybrid drive

The figures are based partially on just running tests of Diesel and electric engines and partially on analytical predictions. The remaining inherent uncertainty w.r.t. the validity of the assumptions applied is expected to be compensated by the enormous improvements, these systems are actually experiencing.

For six 105 kW Wankel Diesel (Figure 7 and Figure 15), or three 220 kW Zoche Diesel (Figure 8) it amounts to about 135 kg.

This minus point compared to the turbine drive is overcompensated by the significantly lower fuel burn (Figure 23), if the helicopter carries a larger fuel safety margin (Figure 22). Without such reserves, the turbine powered helicopter will be lighter (Figure 24 – 1 h VIP transport) with the exception of long range flights.

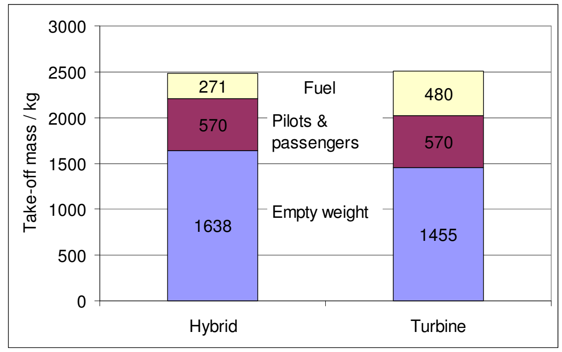

Figure 22 Mass balance for a rescue flight with a fuel reserve for 2,5 h flight

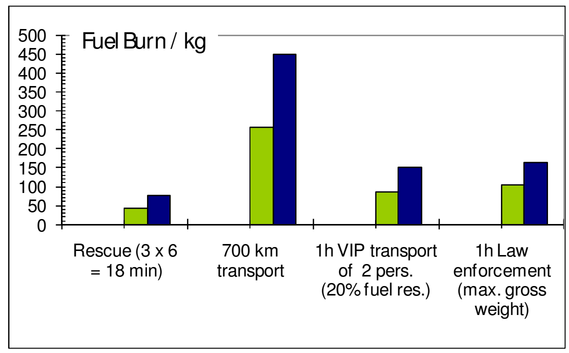

Figure 23 Fuel burn values of hybrid and turbine drive helicopters for different missions, take-off masses see Figure 24

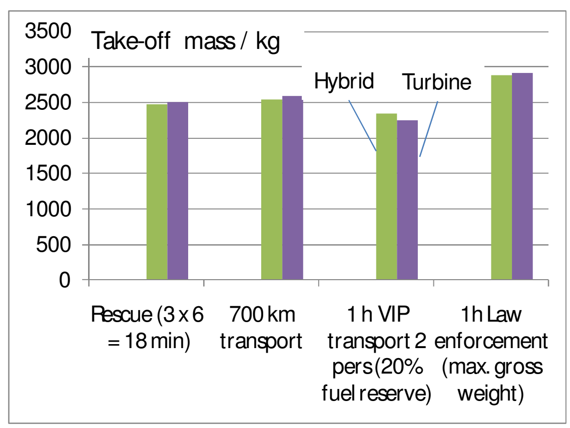

Figure 24 Take-off mass of hybrid and turbine drive helicopters for different missions

Basic assumptions of the computations were:

- For the rescue missions:
  - For safety reasons: fuel for 2,5 h flight endurance on board (typical value for rescue flights, e. g. German Automobile Association ADAC)

- Persons on board: 2 pilots, a doctor and a patient

- In general:

- Identical payloads for hybrid and turbine powered missions,
- 10% transmission loss of the hybrid drive compared to 3% for the turbine drive (see Figure 2),
- For lower rotor loadings: steady power demand minimisation by rpm variation for the hybrid drive,
- Climbs and descents with 65 kt and 6° path angle.

The fuel saving of the hybrid drive amounts to 42 to 45% (Figure 23) for flights with moderate take-off weights (80 to 85 % of max. TOW). For the law enforcement mission with max TOW it's still 36%, the decline of power saving stemming mainly from the impossibility to take advantage of rpm variations due to the high rotor loading.

The take-off weight of the hybrid configuration in Figure 24 is always below the one of the turbine drive with the exception of the 1h VIP mission, in the latter case due to the lower fuel reserve.

This shows that already today, full hybrid configurations may represent a realistic alternative to the conventional turbine powered systems with great advantages in fuel burn. Prerequisites are however, that the new E-motors, generators and Diesel engines under development comply with the respective efficiency expectations.

On the other hand, for the future, even more effective drive systems both in the area of Diesel ICE and electric systems are expected, which represents an important asset of hybrid drives.

10 CONCLUSIONS

From the investigations presented above, a number of results can be deduced:

- A full hybridisation of helicopters using turbo-charged Diesel motors appears possible and reasonable in order to minimise fuel burn, to enlarge design flexibility and to enable family concepts.
- A saving of fuel burn of more than 40% is expected.
- Appropriate turbo-charged Diesel motors, electro motors and generators are under development.
- For flight missions with required higher fuel reserve, hybrid powered helicopters may even have lower take-off weights than turbine driven ones.

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