State of the art of Helicopter Hybrid Propulsion

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***Abstract* — This document presents the state of the art of Helicopter hybrid Propulsion perspectives**

Summary

As done in the car industry, it can be envisaged replacing thermal energy necessary for helicopter propulsion and sustentation by electrical energy. Improvements on electrical technologies allow proposing electrical systems with attractive power to mass ratio to complement the thermal engine providing the mechanical power necessary for the helicopter propulsion. The differences between automotive functions devoted to hybridization and these possible in the case of a helicopter are explained. The different architectures (on turbine or on helicopter side) are reviewed and examples of possible applications on classical helicopters are given, not only the case of AH light helicopter autorotation management improver successfully tested in 2011. The requirements on the electrical system for industrial applications are reviewed: electrical motor and power electronics, cooling systems, energy storage.

State of the art of Helicopter Hybrid Propulsion

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***Abstract* — This document presents the state of the art of Helicopter Hybrid Propulsion. It gives the status of some possible architectures and conditions (technological, economical,…) for practical applications.**

More electrical helicopter, hybrid propulsion

Introduction

As done in the car industry, it can be envisaged replacing partly thermal energy necessary for helicopter propulsion and sustentation by electrical energy. Recent improvements on electrical technologies allow proposing electrical systems with attractive power to mass ratio to complement the thermal engine providing the mechanical power necessary for the helicopter propulsion. The differences between automotive functions devoted to hybridization and these possible in the case of a helicopter are explained. The different architectures (on turbine or on helicopter side) are reviewed and examples of possible applications on classical helicopters are given, not only the case of AH light helicopter autorotation management improver successfully tested in 2011. Complete replacement of the thermal engine by electric could be realistic only when the power to mass ratio of the electrical components will be at the right level, especially for energy storage, which is still far away. The requirements on the electrical system for industrial applications are reviewed: electrical motor and power electronics, cooling systems, energy storage.

I. HYBRID CATEGORIES:

What we call “hybridization” is the use of electrical energy to complement or replace thermal energy for propulsion.

Power can be estimated between tens of kW to help the turbine gas generator to several hundreds of kW if we consider electric motor for rotor direct drive.

By analogy to solutions existing in car industry, new propulsion architectures can be envisaged in helicopter to save fuel or increase power for propulsion and can be classified in several categories depending on electric power levels and organization of the power engines.

Different levels of hybridization can be defined depending on the share of electric power for propulsion (fig1)**:**

- Microhybrid: electric energy is limited to around 50 kW and as such used on the turbine gas generator to give transient assistance (acceleration/deceleration capacities to better master the surge margins), get boost power…for example
- Mild Hybrid means power input to the transmission up to around 300kW, either to the MGB for emergency power in case of turbine failure (improving autorotation of a Singler Engine helicopter for ex.) either to the rear rotor to make it full electric
- Full Hybrid means higher electric power making some flight phases possible with only electric power (cruise for ex.) but not the entire flight; it results that thermal power is required for the other phases and a variety of architectures can be imagined mixing thermal power to produce electric energy, stored or not temporarily in batteries
- Full electric means no thermal power on board for the whole flight, as in some well-known toys or UAVs

And different organizations of power sources:

- Parallel architecture: the electrical power channel provides mechanical power to the rotor in parallel to the thermal engine.
- Serial architecture: the rotor is driven only by electrical motor; the electrical motor is supplied by a generator driven by a thermal engine.
- Power split architecture: electrical motor is connected to the mechanical drive, allowing combination of both energies, adding for mechanical power boost by electric or subtracting to store mechanical energy to electric storage for example.

A mix of these architectures can be implemented between main rotor and tail rotor.

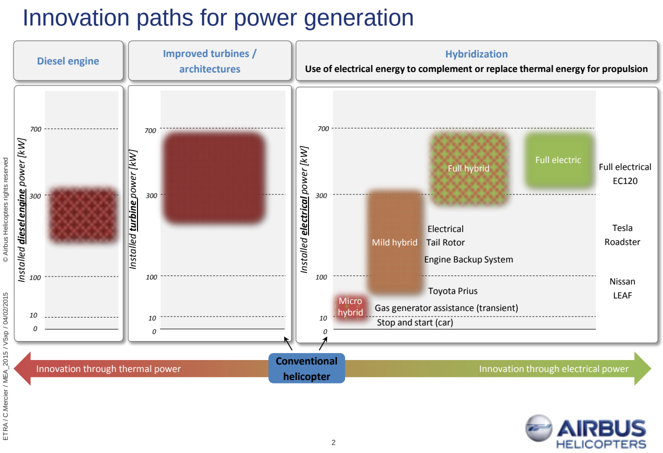

Fig1

II. SPECIFICS OF HYBRIDIZATION FOR HELICOPTERS COMPARED TO AUTOMOTIVE USE

Hybridization on helicopters is different from hybridization on cars as usage and thus power needs strongly differ (fig2)

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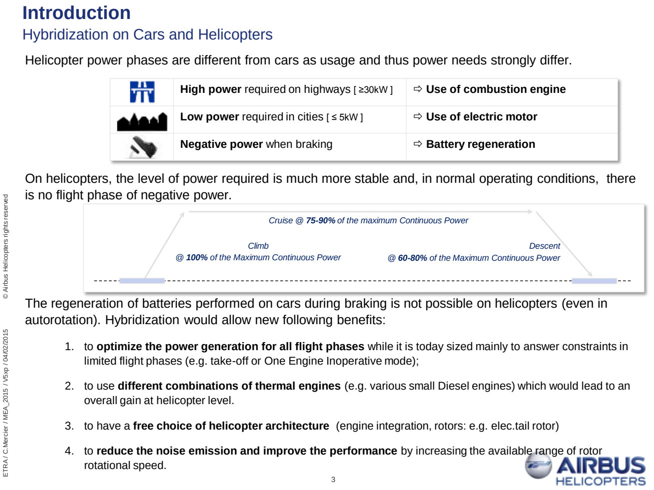

Fig2

On helicopters, the level of power required is much more stable as in cars and, in normal operating conditions, there is no flight phase of negative power.
On cars, the level of required power strongly varies with the use phases:

- High power needed for highway : use of thermal engine
- Low power for city use: use of electric motor with the benefit of high torque at low speed allowing high accelerations
- Kinetic energy recovery during braking resulting in fuel burn reduction, especially in city use

It must be outlined that energy recovery from flight is not efficient in an aircraft. It could be used for faster descents but not for saving fuel.On the contrary to storing energy which is lost into heat in the case of car braking, recovery from flight energy (either kinetic or potential) is a degradation of energy (taking into account the efficiency of storage chain which is way lower than 100%); for example storing energy during autorotation to reuse it for smoother landing is a bad idea because it results in a faster descent…

Nevertheless, helicopter specific characteristics / requirements (multi-engines, emergency situations, flight domain) may justify hybrid power generation solutions.

Current estimates show that for conventional turbine architecture, further improvements may allow reducing fuel consumption by around 15% by 2020 but the optimization of the turbine is becoming more and more complex and as a consequence expensive.
On helicopters, hybridization is not intrinsically green but could enable technologies for green innovation (like Diesel-cycle kerosene fuel piston engines with very low specific fuel burn used at their optimum running point) thus leading to further reductions of the fuel consumption.
The main benefits of hybridization is giving new degrees of freedom and would allow

- to optimize the power generation for all flight phases while it is today sized mainly to cope with constraints in limited flight phases (e.g. take-off or One Engine Inoperative mode)
- to use different combinations of thermal engines (e.g. various small Diesel engines with electric generators electrically linked without the mechanical complexity of multiengine power) which would lead to an overall gain at helicopter level
- to have a free choice of helicopter architecture (engine integration, rotors: e.g. elec.tail rotor)
- to reduce the noise emission and improve the performance by increasing the available range of rotors rotational speed and decoupling main and antitorque rotor speeds.

Contrary to car industry, all technical possible improvements leading to safety and environmental progress (like ABS, airbags, exhaust gases aftertreatment, …) are not yet imposed by regulations and thus do not reach the customer because they impact weight and cost in a competitive environment.
In addition, the weight constraints on helicopters (which are the most demanding of all types of aircraft due to complex aeromechanical laws) are much more important than on cars.

III. ELECTRIFICATION OF PROPULSION SYSTEM

Helicopter propulsion is ensured by main rotor and tail rotor driven by one or several thermal engines. Gear boxes are used to adapt thermal engine output shaft speed to the main rotor

and tail rotor speed. Up to now, this type of architecture is the one implemented in helicopters used with physical persons on board and this article deals with this “conventional helicopter” (main and rear rotors). Electrical propulsion exists for toys and UAVs.
As for fixed wing aircrafts (several demonstrations already done), electrical propulsion solutions can be imagined for helicopters thanks to new technologies emerging in electric domain: electric motors, power electronics and energy storage.

The key factor for the choice, definition and implementation of these hybrid propulsion architectures is the weight and efficiency of the electric system components.
Generally, the electrical system consists in: energy storage device (battery of accumulators or super capacitors or inertial storage device for example), one or several electric motors associated with their power controller, control/monitoring device to manage the electric system in accordance with helicopter power management strategy.
Power-to-mass ratios of these components are now in the range of several kW/kg and will increase in the future thanks to new material: SIC, GaN for power electronics, high temperature material for electric motors, new lithium technologies (Li-S, Li-Air) for energy storage.

IV. SOME EXAMPLES

Among a lot of possible architectures envisaged, some examples are given hereafter. For each architecture the main benefits and drawbacks are listed as well as technological status of electrical equipment available and of requirements on critical characteristics for a practical future application.

A. *Microhybrid on turbine for OEI30s boost:*

For lower powers an input of electrical power to the gas generator of the turbine (for the highest ratings like OEI30s) results in a greater output at the free turbine level and is more efficient than direct electric power to the transmission.
This allows benefiting globally from a better performance for the helicopter; particularly it could be used in case the turbine is at its developments limits for reshuffling helicopter performance.
Present available technology would allow such application.

B. *Engine Backup System (EBS) for Light Helicopter (mild hybrid):*

The supplemental electric system is used to increase maneuverability of a single-engine helicopter during an autorotation landing – which is performed by helicopters in the event of an engine failure: in fact an helicopter flies in autorotation descent and is fully maneuverable, which allows to land safely by applying techniques that single helicopters pilots know and are trained for.
The additional electric motor provides power to the rotor, allowing the pilot to even better control the helicopter after engine failure and then to a safe touchdown.

With the new system the manoeuver executed by the pilot in case of engine failure is identical to what all single engine pilots are used to. The difference is in the increased margins and the easiness of the procedure with the system.
Thanks to the automatic system the reaction time is increased when the failure occurs because the rotor speed droop is slower. This avoids very low rotor speed and a too high descent rate in case of a delayed reaction of the pilot. At the end when landing the power delivered by the system allows stopping the aircraft much easier, to better choose the landing point and to control the ground touchdown much more easily.
The technical characteristics of available motors and power electronics, and one-shot specific batteries are near to allow for a complete system with less than 50kg. Nevertheless, development cost and RC of such system cannot be valued at customer level (as an option for example) because of the loss in payload near to one pax in the absence of a regulatory constraint which would impose it for all manufacturers.

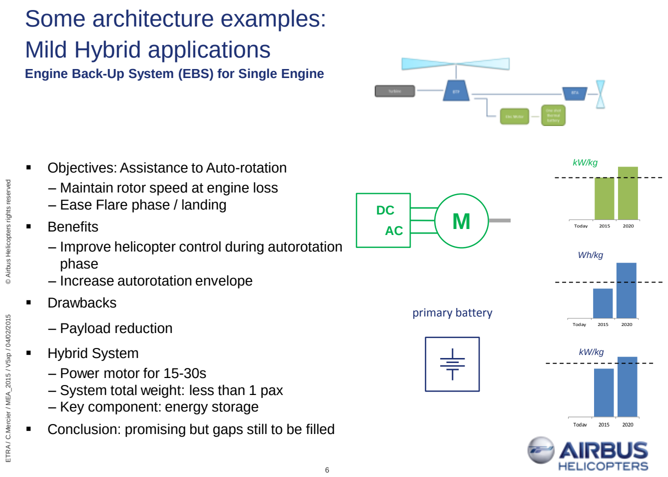

Fig3

C. *Mild hybrid with SIO or SEO*

Turbine Specific Fuel Consumption is minimum at high power. Idea is on a twin-engine helicopter, to put one turbine at the minimum possible idle (Super Idle Operation) or stop it (Single Engine Operation) to save fuel The mild hybrid complement to SIO (or SEO) mode consists in completing the required power level to sustain level flight without any drop of cruise speed. The electrical chain provides the additional power to sustain the level flight while the second turbine is running in SIO or SEO mode. Once the battery runs out of energy, the second turbine is restarted to provide both the power complement to sustain flight and the power to reload the battery.
This architecture helps to save only some % of fuel consumption, with present data of electric systems, compared with conventional architecture, at the expense of complexity.

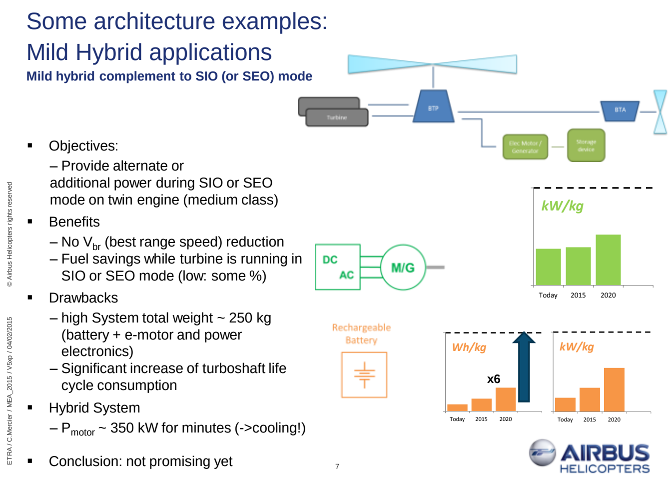

Fig4

D. *Electrical rear rotor (mild hybrid):*

The direct link in speed between turbine, main rotor and rear rotor which leads to difficult tradeoffs between performance and noise for example could disappear if the rear rotor is electrically driven.

Also it seems optimal to drive directly this rotor by an electric motor, and with fixed pitch reverse thrust by reversing the rotation direction.

Nevertheless inertial constraints, aerodynamics, safety requirements lead to additional weight of the order of magnitude of 1 pax which is unacceptable.

In this case the distance to target for the electrical motor (with redundant architecture for safety reasons) is around a factor 5 for weight, not taking into account other detrimental elements like center of gravity backwards position of the system leading to another overweight compensation in the front part of the aircraft.

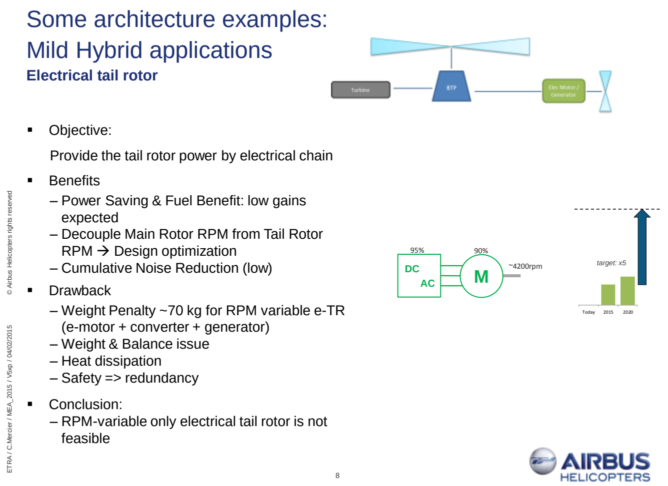

Fig5

E. *Serial with turbine (Full hybrid)*

The example of a single turbine helicopter of Ecureuil size is given, where the turbine is driven at its optimum SFC point so as to minimize fuel burn (whatever the flight case) and electric generator either produces current for the rotor's electric motors either to store energy in a battery.

So that the turbine sizing is minimal and the power complement needed for high power flight cases like takeoff is provided by the battery.

By using today's horizon assumptions regarding the electrical components, the empty weight penalty of this architecture is above 300 kg. On the aerial work mission for example, it is supposed that the turbine can reload the battery on the level flight segment only. However, the weight assessment of the propulsive chain (including the downsized turbine) is way too heavy and prevents the helicopter from carrying fuel at iso take-off weight!

Electrical machines and power electronics are the key components of this architecture. The battery power density should be multiplied by at least 7 to get even with the current Ecureuil performance Downsizing of the turbine is not enough to compensate the strong empty weight penalty. This architecture has no future with the current electrical components characteristics forecasts.

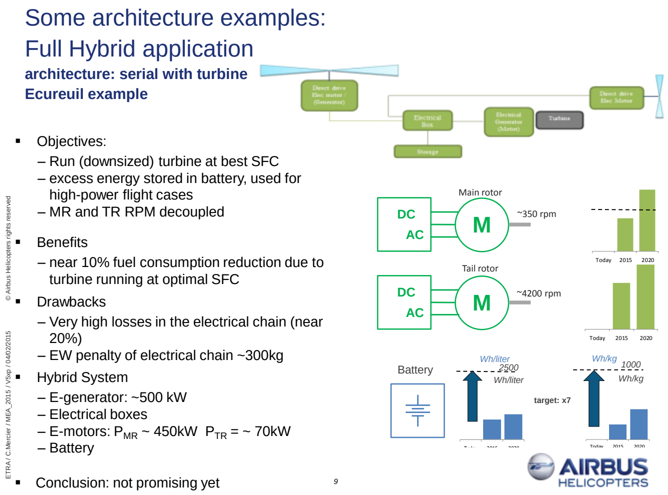

Fig 6

F. *Full electric*

This architecture has been well known in the toys industry where small remote-controlled UAV are manufactured.

However, due to the Froude theory and to other aeromechanical laws, a general rule of thumbs can be applied on the helicopter:

$dP/P \approx 1.1\ dW/W$

where P is the required power and W is the weight of the helicopter.

The main two differences between the toys industry and a real rotorcraft are:

- the increase of required power is clearly not proportional to the increase of weight, due to the aeromechanical laws (factor 3 more at least!).
- in addition, the battery and the electrical motor can occupy the whole space of the toy, whereas it is necessary to keep the same volume of cabin and layout to perform the missions for the real helicopter; the increase of required power is also clearly not proportional to the increase of volume (factor 14 more at least!).

For both reasons (weight scale and volume constraint), it can be seen that if a 10-minute full electrical flight is possible on a small remote-controlled UAV (weighing less than 50 g) with the current battery technologies, the power and energy required are way too much for a 3-ton class rotorcraft aiming at 2 hours of endurance.

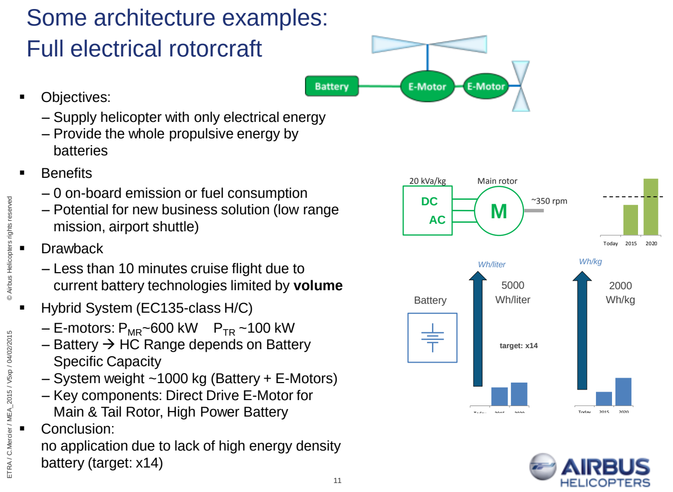

Fig 7

V. THERMAL AND VOLUME CONSTRAINTS

A. Thermal:

A crucial point in hybridization is the cooling of electrical equipment: for short durations high densities power outputs as well for motor as power electronics but also for batteries entail high temperatures which they cannot bear thus a cooling system is required (with liquid and circulation pumps). Only for very short durations (less than 30s, emergency uses like EBS) this can be avoided with use of massic heat capacity for example.

In the case of batteries this can represent additional weight to be added to the gas safety ventings and installation provisions (like supporting crash loads).

B. Volume:

In some cases the battery requires such a capacity that its volume (taking into account its "peripherals" like Battery Management System, internal/external harnesses, crashworthiness provisions, exhaust gases safety outlets, contactors…) presents a problem for installation because it competes with luggage or even passengers rooms.

VI. DISTANCE TO TARGET

Ragone plots show the global results of a comprehensive study of possible hybrid architectures' requirements on main parameters of the electrical equipment (motors/power electronics, batteries) which have to be met at least for performing the same performance of the helicopter (payload,…) with additional benefits (fuel burn essentially).
In red are plotted present physical characteristics of motor (triangle) and batteries (red and orange dots). In green the targets zones.
We can see that we still are quite far from these targets, mainly because of the storage poor weight densities (power, energy, volume) which still need great improvements.

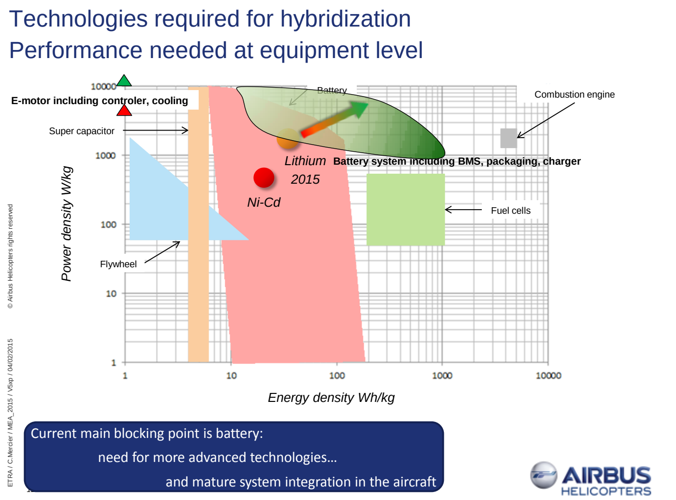

Fig 8

VII. CONCLUSION

Among a variety of hybrid architectures that could be imagined and analyzed taking into account recent progress of electric machinery and storage, mainly emergency electric power source emerges improving the controllability of the helicopter in case of turbine failure. Nevertheless the additional weight and cost of such system remain a bad fit for the customer, especially from an economical point of view. Very significant progress is still needed, especially for the storage device, the battery being the best fit but still far away from the weight/power ratio required for the helicopter which is the most demanding aircraft in terms of lightness. Targets have been defined, associated with specific architectures imagined, the identified benefits of which could be released when they are reached.