DESIGN ANALYSIS FOR HYBRID PROPULSION

S. Bagassi*, G. Bertini*, D. Francia*, F. Persiani*
***University of Bologna**
sara.bagassi@unibo.it;d.francia@unibo.it

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Abstract

Developing green propulsion concepts for aviation requires some changes in standard procedures for the preliminary aircraft design.

Standard design procedures are not readily applicable to aircraft/rotorcraft that use multiple energy sources; innovative concepts like hybrid propulsion systems require new approaches in weight and performance prediction.

In this paper the application of new methods is explored to account for the changes in the governing equations when using hybrid propulsion: a design code allows predicting the performances once the hybrid propulsion architecture is chosen.

Focus is on hybrid propulsion systems based on a diesel heavy fuel ICE (Internal Combustion Engine) combined with an electric motor in a parallel configuration. This study relies on simple structure and material performance indexes, neglects stability and control analysis, and uses very simple aerodynamic models.

1 General Introduction

Increasing air traffic, increasing urbanization and regulatory attention are the most responsible for last few years' need to control the air quality. Since air passengers are projected to grow at a rate of 5 percent per year through 2015, aviation is believed to strongly influence the environmental impact because of aircraft emissions effects on the Earth's atmosphere and climate.

Engine emissions have adverse effects on global warming and local air quality: this is a good reason why unconventional aircraft propulsion systems are investigated, aiming at reducing aircraft emissions and noise [1], [2].

Alternative energy is appealing for environmental, economical and political aspects; the cost of renewable energy has been significantly reduced because of technological advances, while the oil price has an increasing trend.

The most investigated alternative energy sources for aircraft applications up to now are hydrogen [3], [4], [5], solar energy systems [6], electric systems; atomic energy (alternative but dangerous for the environment) is still investigated for space travels [7].

With the energy crisis still looming, initiatives such as More Electric Engine (MEE) and More Electric Aircraft (MEA) are promoted: in this context hybrid-electric power, helping in reducing fuel usage, is considered because of its potential advantages. These mainly concern reduced emissions, increased performance (especially at altitude, since air density does not affect motor performance), lower operating costs, increased safety due to decreased risk of mechanical failures, reduced risk of explosion or fire in the event of a collision and less noise.

Despite several all-electric aircraft exists [8], the installation of an all-electric propulsion system is limited by the energy storage capability; the hybrid electric-fuel propulsion technology seems to be a good compromise between reduced fuel consumption, emissions and high power to weight ratio needed for aircraft propulsion.

Hybrid technology combines the advantages of two or more power sources to create a more efficient propulsion system for a vehicle. While many variants of hybrid systems are available today, most derive from three basic architectures: series, parallel and power-split [9].

Most systems utilize an internal combustion engine as the primary power source and battery packs to power electric motors to be combined to generate power [10].

Usually the ICE is a gasoline engine: this study proposes a diesel engine as the ICE subsystem, the target is to further reduce fuel consumption and emissions with respect to a gasoline ICE. When compared to gasoline engines and turbo-shafts, state-of-the-art diesel engines reach high levels of fuel efficiency; recent improvements in automotive diesel technology have lead to better power-weight ratios. Moreover gasoline suffers from high levels of taxation compared with the JP4, JP8, and Jet (A1) fuels. Furthermore, the low volatility of diesel fuels increase safety. All this explains the renewed interest in diesel engines for aviation.

Revolutionary propulsion systems require the use of unconventional design strategies. In order to implement the hybrid concept, the most relevant aspects of aircraft sizing, impacting on the overall size of aircraft and installed engines, must be adapted to the new technology.

Since the conceptual design phase, the initial estimation of thrust or power required is a primary concern, especially if a new propulsion system is going to be developed.

Therefore, aircraft sizing has to take into account the technologies of the alternative propulsion systems and alternative energy sources. Aircraft design is a highly iterative process: by incorporating a hybrid propulsion system, new design parameters enlarge the domain of feasible solutions and the complexity for finding an optimal solution increases further. Unmanned Aerial Systems / Remote Piloted Aircrafts (UAS/RPA) are the most promising systems for taking advantage from hybrid propulsion technology.

Up to now the approach to the sizing of RPAs has been based on conceptual design methods usually used on conventional aircrafts. However the traditional methods cannot capture the full potential of hybrid UAS/RPAs. The design process for traditional aircraft using internal combustion engines can be used as a reference framework but must be modified properly.

The hybrid-electric propulsion development needs a new conceptual design tool for sizing aircraft, that helps engineers in understanding the expanded feasible solutions, for hybrid-electric UAS to meet different mission needs [11]. The traditional aircraft sizing methods can be modified and applied to dramatically innovative aerospace concepts that use different types of energy [12]. The starting point of the work presented in this paper is described in [13] and it is developed elaborating on constrained static optimization formulation to study hybrid diesel-electric propulsion system design.

2 Methodology

The adopted approach is based on the comparison in terms of performances, consumptions and weights between two configurations of the same aircraft equipped with two different propulsion systems: a traditional diesel engine versus a parallel hybrid diesel-electric propulsion system. The parallel hybrid diesel-electric propulsion systems consist in a diesel internal combustion engine, an electric motor, a rechargeable battery pack and a propeller.

2.1 Hybrid conceptual design

The method consists in three main blocks: a weight estimation module, an optimization module and a post- processing module.

The weight estimation module estimates the weight fractions of the hybrid engine aircraft (*Hybrid Configuration*) starting from data of diesel-engine aircraft (*Reference Configuration*).

The input data are referred to the Reference Configuration and consist in aircraft data, mission data, wing geometry constraints and aircraft component mass. The list of input data is reported in Table 1.

Table 1. Input data list

Reference aircraft data:	*Mission data:*
Wing efficiency	Takeoff altitude
Max. lift coefficient	Mission altitude
Stall speed	Maneuvering speed
Propeller efficiency	Ref. cruise speed
Mechanical efficiency	Ref. SL rate of climb
Battery spec. energy	Ref. TO ground dist.
Specific motor power	Reference range

Wing geometry constraints:	*Reference aircraft component mass:*
Maximum wing area	Max. take-off weight
Minimum wing area	Fuel weight
Maximum wingspan	Engine weight
Minimum wingspan	Payload weight
	Empty weight
	Battery weight

Starting from these input data, the weight of the glider is calculated as the difference between the empty weight and the engine weight in the Reference Configuration.

Then the statistical data from [13] are used in order to calculate weight fractions for each mission segment. The output of this module is the estimate take-off weight to be used in the following iterations.

Input data set in the first module and the estimate take-off weight are passed to the second module.

The main function of this module is optimizing the required power for cruise. The function (1) is minimized under stall limit constraint (2) and structural limit constraint (3).

$$P = \frac{1}{\eta_{\mathrm{Prop}}\eta_{Mech}}\left(\frac{1}{2}\rho V_{cr}{}^{3} S c_{D0} + \frac{KW}{\frac{1}{2}\rho V}\frac{W}{S}\right) \tag{1}$$

$$\frac{W_0}{S} - \frac{1}{2}\rho V_{stall}{}^{2} c_{L,\max} \leq 0 \tag{2}$$

$$AR - \left(\frac{2nW_0}{\rho V_a{}^{2} S}\right)^{2} \frac{1}{c_{D0}\pi e} \leq 0 \tag{3}$$

Where:

$K = \frac{1}{\pi e AR}$

e	Oswald efficiency factor
c_{D0}	Zero-lift drag coefficient
$c_{L,\max}$	Maximum lift coefficient
V_{cr}	Reference cruise speed
V_{stall}	Stall speed
V_a	Manoeuvring speed
η_{Prop}	Propeller efficiency
η_{Mech}	Mechanical efficiency

Based on the results of this routine, the performances are calculated and the power excess needed to meet the requirements in terms of Take-Off Distance and Rate of Climb is computed in order to determine the Hybridisation Factor of the Hybrid Configuration.

In the post-processing module the main parameters for both Reference Configuration and Hybrid Configuration are worked out and processed in order to quantitatively compare the two configurations.

3 Results and discussion

The object of the study is an UAV's conceptual design. The reference design is a MALE UAV equipped with an ICE Diesel engine. The study goal was retrofitting the propulsion system. The original diesel engine had to be replaced by a smaller diesel engine, combined with an electric motor to have a similar aircraft with a hybrid-electric propulsion. The diesel engine propulsion is a good compromise to obtain energy more efficiently; the diesel hybrid-electric should lead to an even more green propulsion.

The case study application of mild-hybrid would have to sacrifice an amount of endurance to allow the batteries to be carried on board instead of fuel. Although the electric energy from the battery was used more efficiently than fuel, more energy could be stored in an equal mass of fuel.

The conceptual design goal of the hybrid propulsion was to obtain the same GTOW of the original aircraft, while increasing the payload trading with a lower endurance.

Having the same GTOW is possible to compare the results to the original configuration, while the aerodynamic design and the AC structures do not require major changes.

See Table 2 and Table 3 to view the results of the procedure. The input data are the original aircraft design parameters to be kept constant and a certain number of variables of the hybrid propulsion.

We can observe different distribution of the weight fractions. These different distributions are reported in terms of source energy components weight fraction (Figure 1) or in terms of aircraft component weight fraction (Figure 2).

The battery mass needed was still too large for enough fuel to be carried on board to support the original range. The amount of fuel mass lost is due to the lower range and the more efficient propulsion: fuel consumption per NM of range drops from 0.3125 to 0,1 kg/NM.

Table 2. Weight components for the Diesel Configuration vs the Hybrid Configuration

Weight	Unit	Original UAV	Hybrid-electric UAV
Max takeoff weight	kg	1200	1132
Fuel weight	kg	250	50
Engine weight	kg	200	141
Payload weight	kg	140	182
Battery weight	kg	10	134
Glider weight	kg	600	600
Electric Motor weight	kg	0	25

Table 3. Performances for the Diesel Configuration vs the Hybrid Configuration

Performance	Unit	Original UAV	Hybrid-electric UAV
Engine	kW	121	104
Wingspan	m	12	12
Wing Area	m^2	11	10,5
TO Distance	m	500	483
ROC	m/min	304,5	304,5
Range	NM	800	500
Wing loading	kg/m^2	106	107,7
Cruise speed	m/s	65	65
Motor Power	kW	0	56
Type of fuel	NA	Jet A1 JP8	
HYBRID FACTOR	0	0,36	

Observing Figure 1, the battery weight fraction gain was similar to the fuel and engine weight fraction drops. The electric motor was designed to supply the surplus power needed to the take off, while in cruise the UAV was powering by the smaller ICE diesel engine.

One of the initial problems of aircraft was the oversizing of engines at cruise. Since there were demonstrated fuel savings, the hybrid should possess the same savings regardless of the range sacrificed. Investigating the UAV further gave insight for the design considerations needed for hybrid UAVs.

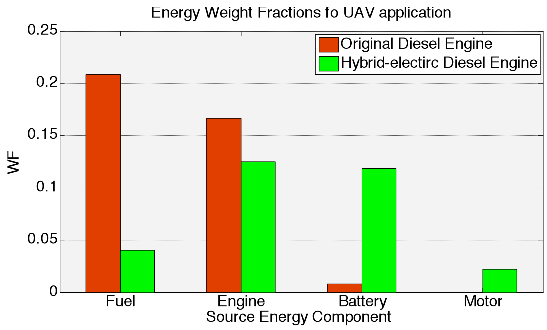

Fig. 1. Energy weight fractions for Diesel Configuration are shown in red while energy weight fractions for Hybrid Configuration are shown in green.

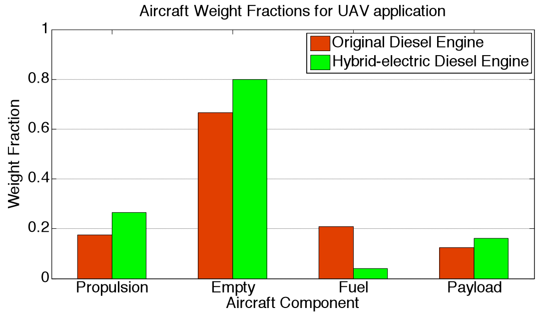

Fig. 2. Aircraft weight fractions for Diesel Configuration are shown in red while aircraft weight fractions for Hybrid Configuration are shown in green.

The flying qualities of the UAV were consistent with the changes made to the performance requirements. Using different altitude profiles the following graphs report typical curves: Figure 3 reports the diesel engine power required at sea level and at altitude.

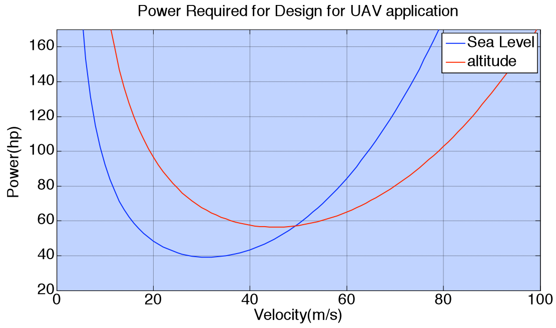

Fig. 3. Diesel engine power required at sea level and at altitude.

To achieve a reasonable climb rate, the reference UAV needs a 121 kW diesel engine. The hybrid design needs a 104 kW diesel engine to maintain steady level un-accelerated flight (SLUF) at cruise altitude. Figure 4 compares the difference between the engine's ability to climb, against the augmented power provided by the motor, at sea level and at the cruise altitude.

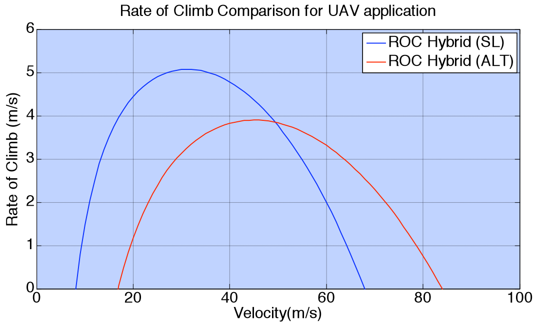

Fig. 4. Rate Of Climb for the hybrid configuration at sea level and at altitude.

4 Conclusions

The hybrid conceptual design code is based on a modified weight fraction method. The building of an aircraft's overall weight can be obtained by the component weight fractions. For un-conventional designs the weight distribution was significantly different, because of the different energy sources; the main factor is the battery mass needed to power the electric motor. Comparing the weight fractions before and after hybridization, the UAV case study has shown that was sacrificed a percentage of range, while gaining a lot in fuel consumed per mile of range. In future battery specific energy can be improved so less range would need to be sacrificed.

The electric energy stored in batteries, it can be used by an electric motor with 92% or greater efficiency. If we consider that the efficiency of diesel engines is around 40%, the high specific energy of the chemical fuel is wasted on thermal inefficiency. Specific energy of batteries only needs to reach 40% of hydrocarbon fuel's specific energy to be just as effective. If more fuel is replaced by batteries the efficiency of the energy stored on-board would increase. The mild hybrid-electric design demonstrated fuel saving potential and improved the overall efficiency of the energy delivery. The improvement of the UAV propulsion design to satisfy multiple mission profiles seems to be supported by this research. If we consider that the electric power is independent from altitude, the added performance provided by the motor could get the flying platform to altitude quickly and provide boost power when requested.

4.1 Further considerations

For better understanding of the advantages of hybrid propulsion, more simulations need to be run so the mild hybrid-electric system can be more effectively used for specific mission profiles. Takeoff and climb were not the only mission segments that could benefit from the added power source. During a typical reconnaissance mission a UAV may perform more climbs, sustained turns, slow flight, and missed landing scenarios that may need extra power. Keeping the diesel engine at its optimal operating point, more throttle would require power from the electric motor instead of increasing the fuel usage. To simulate these conditions, different fuel fractions can be calculated for each mission taking into account the different segments of the mission. The necessary motor power dictates how much energy is needed from the batteries. Summing each mission segment from takeoff to landing the total fuel mass and battery mass can be determined. Expected results are that added fuel savings would result. In real applications the physical integration of the engine, motor, and battery is a challenge. In automotive industries multiple suggestions have been proposed to the mechanical configuration of the components. In next studies we aim to analyze the performance of the transmission system, in terms of additive torque between power sources. Additive torque between the components is essential for the conceptual design code to be accurate. Other issues arise when we need to define the hybrid propulsion layout configuration; so we need to place each component into the aircraft. Each component mass must be placed appropriately so the center of gravity location yields a stable aircraft. The obvious decision would be to place the engine and motor in a single mechanical unit. The battery mass could be split by using multiple batteries to get an acceptable weight balance. Future work will be needed to integrate the power sources using an optimized transmission, and determine the proper placement of each component in the aircraft.

References

[1] Garot J.M, The Future Air Transport System in Europe: Vision and Perspectives. *AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Y*, 2003.

[2] Sehra A K and Woodrow W, Propulsion and power for 21st century aviation. Progress in Aerospace Sciences, Vol 40, Issues 4–5, May–July 2004, pp 199–235.

[3] Westenberger, A., Hydrogen Fuelled Aircraft. *AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Y*, 2003.

[4] Brand J, Sampath S.F, Potential Use of Hydrogen in Air Propulsion. *AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Y*, 2003.

[5] Renouard-Vallet G, Saballus M, Schumann P, Kallo J, Friedrich K.A, Müller-Steinhagen H, Fuel cells for civil aircraft application: On-board production of power, water and inert gas. *Chemical Engineering Research and Design*, Vol 90, Issue 1, January 2012, pp 3-10.

[6] Vashishtha V.K, Kumar A., Makade R., Lata S. Solar power the future of aviation industry. *International Journal of Engineering Science and Technology (IJEST)* Vol. 3 No. 3 March 2011, pp. 2051-2058.

[7] Bennett G. L, Space Nuclear Power: Opening the Final Frontier. *4th International Energy Conversion Engineering Conference and Exhibit*, 2006.

[8] Gohardani A.S, Doulgeris G and Singh R, Challenges of future aircraft propulsion: a review of distributed propulsion technology and its potential application for the all electric commercial aircraft, *Progress in Aerospace Sciences-Elsevier*, Vol 47, Issue 5, July 2011, pp 369-391.

[9] Momoh O.D and Omoigui M.O, An overview of hybrid electric vehicle technology. *Vehicle Power and Propulsion Conference,* 2009, pp. 1286 – 1292.

[10] Glassock R.R., Hung J.Y., Walker R.A. and Gonzalez L, Design, modelling and measurement of hybrid powerplant for unmanned aerial systems (UAS). *5th Australasian Conference on Applied Mechanics*, 10-12 December, 2007, Brisbane, Australia.

[11] Harmon F.G, Frank A.A and Chattot J.J, Conceptual Design and Simulation of a Small Hybrid-Electric Unmanned Aerial Vehicle. *Journal of Aircraft*, Vol. 43, No.5, Sept-Oct 2006, pp 1490-1498.

[12] Hiserote, R., Harmon, F., Analysis of Hybrid-Electric Propulsion Systems for Small Unmanned Aircraft Systems, AIAA-2010-6687, AIAA's 8th International Energy Conversion Engineering Conference, Nashville, TN, July 25-28, 2010.

[13] Raymer, D.P., Aircraft Design: A Conceptual Approach, 1st Edition, American Institute of Aeronautics and Astronautics, 1989.

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