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Modelling the Fuel Consumption in Hybrid and Electronic Airplanes using Matlab Aerospace toolbox

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***Abstract*— With the rise in popularity of electric cars more types of vehicles are adapting electric drives. In the case of airplanes the standards are higher than in the case of cars so the emphasis of research and innovation is greater. This paper presents a list of the challenges electric aircrafts face and their potential solutions. The paper describes the most important elements of electric and hybrid aircrafts. Comprehensive model was created taking into account the criteria set for hybrid and electric aircraft. With the aid of the model the effect of the most important components on efficiency can be assessed. One modelling approach in Matlab Simulink environment is also described. For the modelling the Matlab Aerospace toolbox is also used.**

***Keywords*— hybrid aircrafts, Matlab Aerospace toolbox**

I. INTRODUCTION

With the increasing of the greenhouse effect even more concern is placed on the reduction of harmful emissions in air travel. Based on the Strategic Research & Innovation Agenda (SRIA) [1] of the Advisory Council for Aeronautics Research in Europe (ACARE) the International Air Transport Association (IATA) [2] and the European Commission (EC) [3] announced long-term environmental protection goals. The plans may seem ambitious looking at the technologies currently being used. The main focus is on the reduction of the energy needed for propulsion. The goal is a 30% decrease in the needed propulsion and power by 2035. A 70% decrease in carbon dioxide emission is the goal by 2050. By 2020 an estimated 20% decrease is expected in the energy needed for propulsion and power compared to the reference data from 2000. The efficiency of the drive holds the key to the greatest reduction in carbon dioxide emissions [4]. Figure 1 shows the efficiency of currently used drives and the goals set by the strategy and also shows the total overall efficiency of the airplanes drive during flight ηov (overall efficiency) compared to the reference year of 2000. The graph shows two types of efficiencies the product of the two gives the aforementioned overall efficiency. The vertical axis shows the efficiency of the propelling force ηpr (propulsive efficiency) while the horizontal axis shows the internal or thermal efficiency ηin.

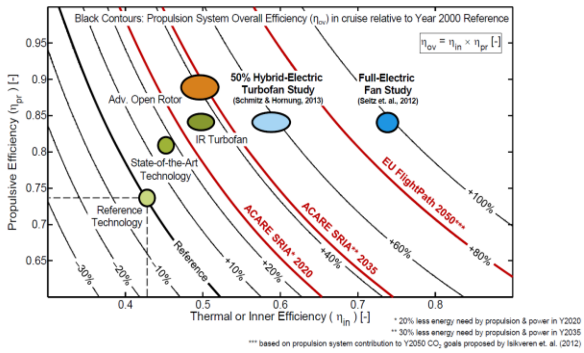

Figure 1. Propulsion systems overall efficiency

The graph shows that the goal of ACARE by 2035 is to increase total efficiency to 43%, while setting an 80% increase by 2050, which can be achieved by improving both types of efficiency. The current state of the art engines efficiency is 15% above the efficiency of the year 2000 baseline model. Improving on the advanced gas turbine based concept [4] we can expect an efficiency of about 50% or more which fulfils the efficiency goals set by 2020. The greatest increase in propulsive efficiency can be expected from the Open Rotor (OR) and the Turbofan drives. Figure 1. shows the efficiency of hybrid and fully electrically driven air funnel propeller drives [5][6][7]. From the studies we can see that electrifying the turbo drives efficiency of 50% is expected to reach the efficiency goals of 2035, while converting to a fully electric drive is expected to yield an efficiency of nearly 100% [8][9].

II. MEASURE OF HYBRIDIZATION

When having more than one drive in a vehicle the tuning and handling of them becomes a real challenge. In the case of hybrid vehicles, the electric drive needs to connect to the system so that it provides maximum efficiency. Because of this some new variables come into play [13]. One of the key variables is the measure of energy hybridization which is the ratio of the electric energy to the total energy.

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$$H_E = \frac{E_{bat}}{E_{tot}} = \frac{E_{bat}}{E_{bat} + E_f}$$

Where E_{bat} is electrical energy and E_f is the energy coming from the fuel. The measure of energy hybridization is not an ideal indicator since the specific energy of the fuel is much greater that the specific energy of the battery while the efficiency of electric drives is far greater than the efficiency of gas turbines. Because of this reason we use the power hybridization indicator as well [10].

$$H_P = \frac{P_{el}}{P_{tot}} = \frac{P_{el}}{P_{el} + P_{th}}$$

Where P_{el} is the power of the electric motor and P_{th} is the power of the gas turbine. For conventional airplanes the measure of hybridization is 0 since all the energy comes from the burning of fuel: $H_E = 0$ and $H_P = 0$. In the case of turbo-electric airplanes all energy is all propulsion is from electric motors that are powered by gas turbines giving us $H_E = 0$ and $H_P = 1$. In the case of fully electric airplanes we have $H_E = 1$ and $H_P = 1$. This means that all energy is from the battery and all propulsion is from electric motors. In practice this indicator is not always applicable since an airplane with a large electric motor that is used sparsely gives a large power hybridization value while in reality during flight it's only hybrid for a short time.

For this reason another parameter the produced power ratio [14] (Φ) is used which is the ratio of the power exerted by the electric motor and all the power exerted during flight.

$$\Phi = \frac{E_{em_{tot}}}{E_{pow_{tot}}}$$

In the case of a traditional airplane Φ=0 while at a fully electric airplane Φ=1. A further example Φ=0.4 means 40% of the energy for flight came from the electric drive and 60% from the gas turbines.

III. KEY ELEMENTS OF THE HYBRID AND ELECTRIC AIRPLANES

A. *Energy Storage*

Energy storage is the most crucial criteria when designing a hybrid airplane. Traditional aircraft use fuel with a far larger specific energy (12000-13000 Wh/kg) [12] [15] than in the case of batteries. The specific energy of batteries needs to increase in accordance with economic and ecological expectations. Figure 2 shows a Ragone diagram which is used to describe the current levels of batteries where the specific power and energy are shown on a logarithmic scale.

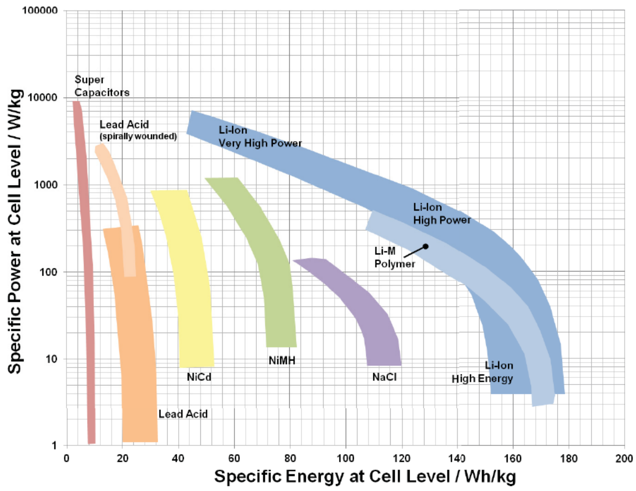

Figure 2. Ragone diagram for specific Energy and Specific Power [15]

Lithium-ion and Lithium-polymer batteries are the most used batteries on the market thanks to the ideal placement of both characteristics (Figure 2.). The power of the Lithium batteries is determined by the materials used for the electrodes. The state of the art batteries positive electrode is made of Lithium-metal-oxide (mostly cobalt and manganese) while the negative electrode is made of graphite, these batteries have a specific energy of 300 Wh/kg and have a specific power of less than 100 W/kg. These values are not enough for a typical flight. For example a Tesla Model S P85 electric car has a Li-ion ESD (Energy Storage Device) which has a maximum continuous power of 311W and a total stored energy of 85 kWh. The mass of the battery is 540 kg so it has a specific power density of 575 W/kg and a specific energy density of 157 Wh/kg.

In the studies made by the Safran company [17] they show that a smaller airplane would need a battery with a specific energy density of 500 Wh/kg while a bigger passenger carrier would need between 600 and 750 Wh/kg. The above mentioned Li-ion and Li-polymer batteries provide a good basis for the electric and hybrid cars of our age, but are inadequate for hybrid airplanes. Currently Lithium-Sulphur batteries are the most promising energy storage devices [19], because compared to Li-ion batteries they have a large specific energy. The theoretical maximum is 2567 Wh/kg at 2.2 volts. Currently the OxisEnergy company [16] sells these type of batteries which have a specific power of 300 Wh/kg and plan to double this value in the next five years. These batteries are characterized by a Lithium anode and a Sulphur cathode. In the discharge process the lithium reacts with the sulphur to become Li_2S, which in the process of recharging breaks up into its components. The problem with Li-S batteries is their lifetime currently they last for 500-1000 charging cycles, the manufacturer plans to increase this to 1500-2500 cycles in the next few years. On a positive note they have a low production cost of about 250 euros/kWh compared to Li-ion which have a price of 475 euros/kWh.

Following the trend of the Li-S batteries by 2021 we can expect a specific energy of about 500 Wh/kg, 650 Wh/kg by 2030 and 1000 Wh/kg by 2040. These values are adequate for use in hybrid airplanes.

B. *Electric motors*

The second main pillar of hybrid and electric vehicles is the electric motor. Thanks to electric and hybrid cars these have also advanced quite a bit. More power with less loss, weight and size these are the most important criteria for flying applications. The Siemens company has made excellent headway in this field thanks to its intense research strategy [17]. These motors have an efficiency of 95% and are quite light, their power density (Wsp) exceeds 6 kW/kg. It can be easily redesigned for smaller or larger applications, making it ideal for large or small aircraft.

Siemens made their SP260D induction motor (Figure 3.) which has a maximum continuous power of 260 kW at 2500 rpm and a total mass of 50 kg. The power density of this motor is at least 5 kW/kg. This motor has been installed and tested on the Extra 330 LE airplane.

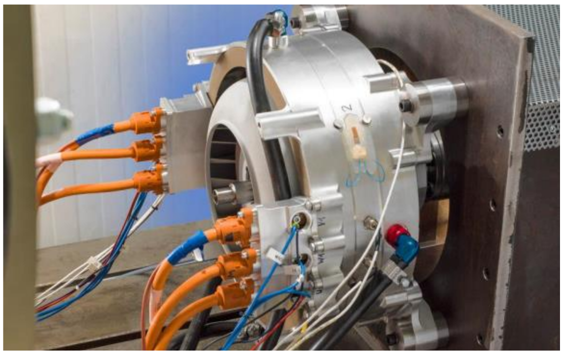

Figure 3. Siemens SP260D electromotor

In future automotive and aircraft applications the so called high temperature superconducting (HTS) motors can be used. These motors cooled by liquid nitrogen can have an internal resistance of 0 thus having high power density. Their only drawback is that they need constant cooling which uses mostly liquid nitrogen. Currently available HTS motors fall short of expectations having 30 kW-s of power with a 110 kg engine [18]. Their power falls short compared to the SP260D, but HTS motors are relatively new and research shows that a power density of 20 kW/kg is possible.

C. *The material and structure of an airplane*

Other than the mass of the above-mentioned motor and battery one of the most important parameters is the mass of the fuselage and its structure.

Modern airplanes use carbon and glass reinforced composites [20]. The two components of the composites are the matrix and the reinforcement. The composites were developed for combining the benefits of the different materials' advantageous physical parameters. The first "modern" composite (used even today) was the textile-bakelite that is a phenol formaldehyde resin enhanced by textile fibres. The resin is a really rigid, frangible and weak plastic and only the enchantment with natural textile fibres made it suitable for wider industrial applications. The first composite applied in aircraft industry in bigger amount was a one-direction strip named GORDON AEROLITE developed by Aero Research Ltd. that was an untwisted line string impregnated by phenol resin in the '30s. The next step was the "marriage" of the high strength fibre glass and the polyester resin that was used first in 1943 for the rear part of the fuselage of a trainer plane (Vultee XBT-16) made in the USA with a honeycomb structure sandwich panel. In the aircraft industry appeared the epoxy-resin matrix materials that were first reinforced with fibre glass then carbon-, graphite- or aramid-fibres, boron-fibres, ceramic fibres or the combinations of them [21].

Several have been developed in the history of aircraft design. With the advance of airplanes the position of the wings, engines, rudders changes even to this day. Several studies were conducted to explore which configurations are most optimal for hybrid and electric aircraft [23].

IV. Developing an Optimization Model

The topics discussed in previous subchapters all contribute to the optimization of hybrid and electric airplanes. Several other parts could also contribute to the optimization process (such as drive electronics, choosing the optimal cable size etc.), however we will omit these. During our research we aimed to create a model that takes into account the most important facets of optimizing the efficiency of an aircraft. These facets are: the architecture of the drive, energy storage, electric motor selection, the structure and material of the aircraft. These are the facets that impact the basic maneuvers and thus the flight duration, quality of flight, safety, fuel consumption and efficiency (Figure 4.).

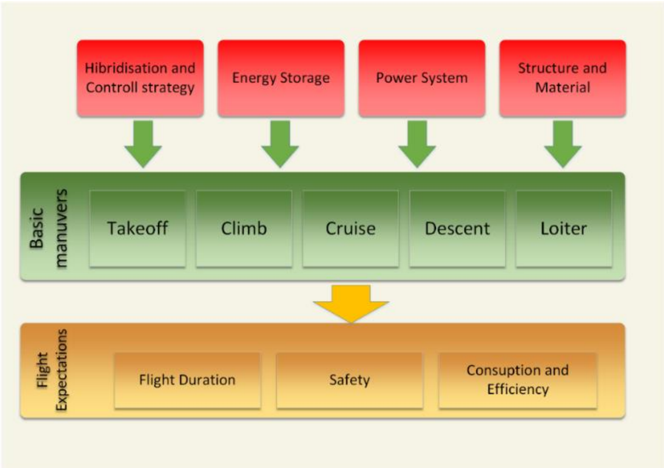

Figure 4. Illustration of 15 out of a total of 35 proposed concepts

In the modelling of fuel consumption usually only 5 base manoeuvres are taken into consideration [11]:

- Takeoff: this is simulated to have a realistic power requirement and energy consumption, by considering the two phases of ground run and airborne acceleration
- Climb: the aircraft climbs from airport altitude to cruise altitude and accelerates from takeoff to cruise speed

- Cruise: this phase is carried out at a constant altitude and true airspeed
- Descent: the dual of climb phase, it starts at cruise speed and altitude and ends at loiter speed and altitude, using the same strategy considered for climb
- Loiter: this phase is considered both for possible deviations and for actual hold above the destination airport

With the optimization of these base manoeuvres we can impact flight time, safety and fuel consumption. The hypothetical model tries to optimize by taking into account in a simplified way the effects of the base components on hybrid and electric airplanes fuel consumption. Individually it wouldn't try to classify their effects since can be several future solutions which effects on fuel consumption are unknown.

V. MATLAB AEROSPACE TOOLBOX

Matlab aerospace toolbox gives tools and ability to breaking down the route and flight condition of aviation vehicles and presenting their flight utilizing standard cockpit instruments or a simulation. It allows the import of Data Compendium (Datcom) files into MATLAB® to facilitate aircraft optimal design and fuse approved condition models for environment, gravity, wind, and magnetic field. You can assess vehicle movement and direction utilizing aerospace math functions and arrange reference frame and coordinate transformations. You can picture the vehicle in flight legitimately from MATLAB with standard cockpit instruments and utilizing the pre-fabricated FlightGear Flight Simulator interface.

Using the aerospace toolbox we can import or define our own Datcom file of aircrafts and tweak parameters for wingspan engine power and placement, etc. Running simulations with varying parameters for wings lets us optimize for wing span and lift, while still checking if the handling characteristics stay within acceptable vales as seen on Figure 5 and 6. While it is generally true that optimizing wing span will decrease fuel consumption a lot more can be achieved by creating a better battery management system since this can always be tuned to a specific aircraft design, furthermore it can also improve existing designs.

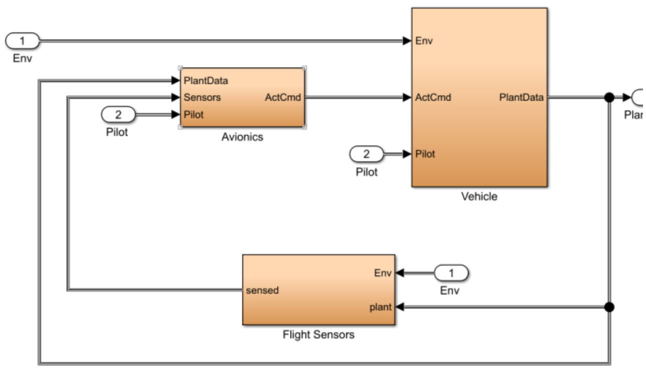

Figure 5. Simulink model of airplane using aerospace toolbox blocks

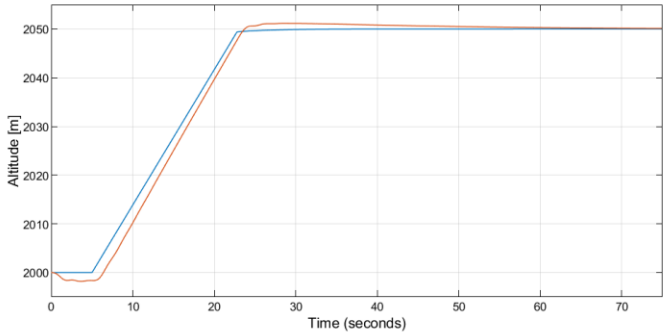

Figure 6. Flight response of modelled aircraft so commanded altitude change

VI. SIMULINK MODELL FOR THE SIMULATION HYBRID AIRPLANES

According to Motapon et al [22] modelling a hybrid electric vehicle requires models for the following subsystems: Fuel-cell/generator, battery, supercapacitor, DC/DC converters, DC/AC converter, load. Using the fuel cell as the main energy source we drive the load which in this case is the 3 phase AC induction motor. When the required power amount changes the electrical energy is stored in the battery and the supercapacitor (figure 7). The energy provider and energy storage devices have different characteristics for the available power they can supply, it is necessary to manage the routing of electrical energy that the components do not wear out too quickly.

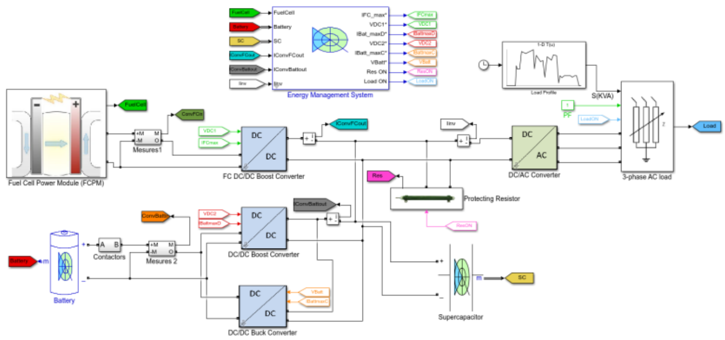

Figure 7. Energy management system for hybrid electric vehicle

As mentioned before the fuel cell/generator is our main power source. In the case of a generator it has an ideal range of RPM-s where energy conversion is most efficient. Naturally we aim to run the generator at this speed, however this won't always meet the power demand this is when it will need to store the excess energy in the battery or the energy needs to be supplemented by the battery. Since the battery has a rated number for discharges/recharges it is unwise to overtax the battery with constant charging this will lead to quickened battery decay. To combat this supercapacitors are used which have a lower energy density then the batteries, but can be charged and discharged practically infinite times and they can supply a much larger amount of current to the load when needed. This is ideal for the short power spikes that are needed at acceleration. The management of these subsystems needs a controller, ideally the capacitor is needed for only short power bursts, the battery needs to discharge only when the supercapacitors require recharging and the generator can’t handle the load. The batteries should only be charged when they reach a critical level to maximize their lifetime. Various control schemes have been proposed for this task. Since it is difficult to come up with a mathematical model to describe this problem a fuzzy controller seems like a most reasonable candidate. Some experiments have also been made with classical PI controllers for this task. The controller monitors the state of charge of the battery system. When the battery state of charge is above the reference, the power coming from the generator is low, and the battery provides its full power. When the state of charge is below the reference, the generator provides almost all of the power. The PI gains are tuned online for a better response.

Since this control problem is difficult to describe mathematically the logical conclusion is a fuzzy controller. With its IF-THEN rule set it is more robust to measurement imprecisions than a PI controller. The main advantage of this controller is that the change in the battery state of charge is trending towards zero. But a fuzzy controller is required which is computationally expensive.

Our suggestion is a simple state based controller where the high frequency load is handled by the supercapacitor, and the low frequency load is handled by the generator. While the battery state of charge is kept between a high and a low state with a bang-bang controller. This proposal can be seen on figure 8.

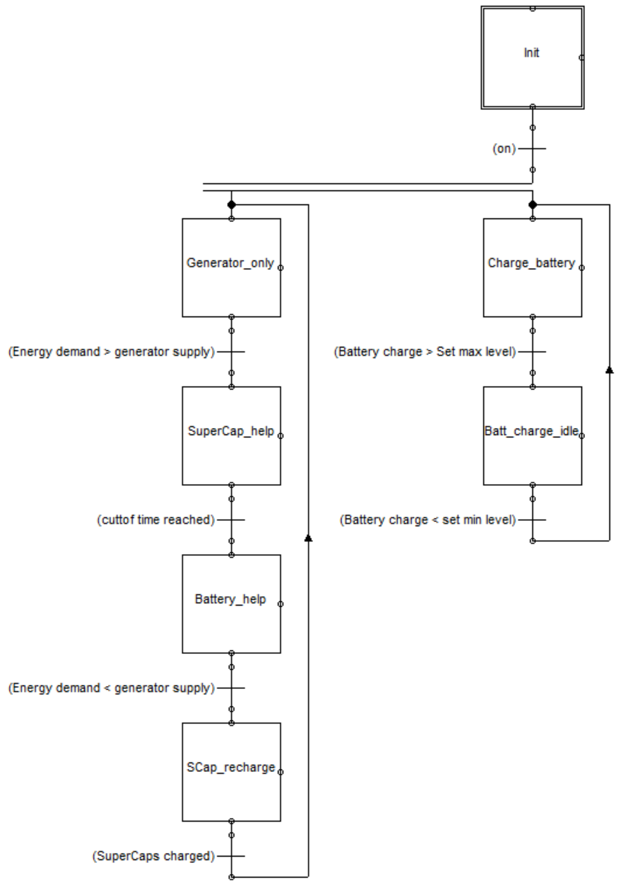

Figure 8. Proposed energy management control scheme for hybrid electric vehicle

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