HYBRID DRIVE TRAINS FOR LIGHT AIRCRAFTS

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Abstract: *In this paper, the concept of a hybrid drive train for light aircrafts is presented. The benefits of the drive train are discussed by the particular example of the transformation of a well-known Cessna 172 to a hybrid aircraft.*

1. Introduction

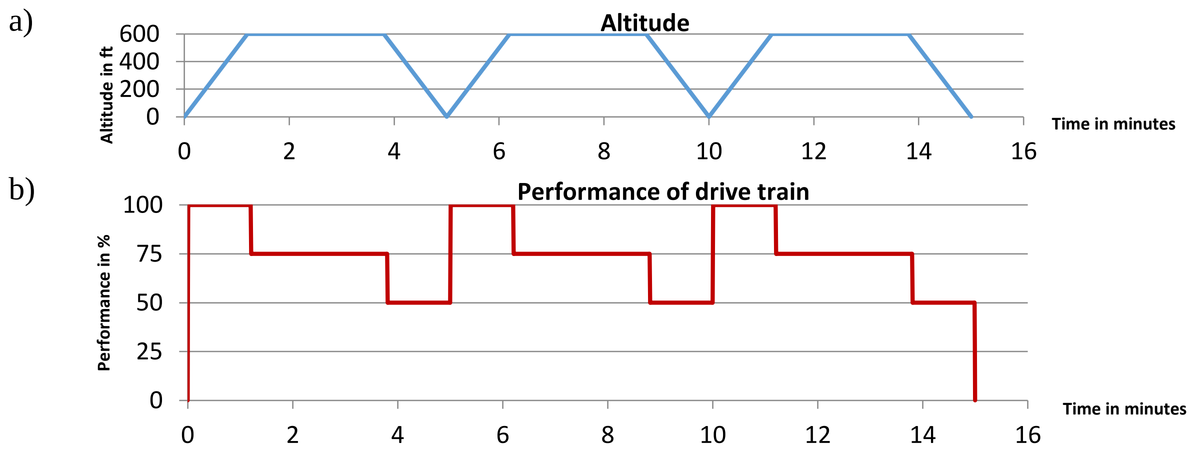
Nowadays available powered aircrafts of all sizes use fossil liquid fuels as power source. Due to rising fuel prices, efficiency issues and environmental awareness especially in matters of carbon dioxide (CO_2) emission and noise new drive train concepts for aviation are an interesting field of research. On the other hand, innovation in aviation is difficult because of legal and technical requirements.

Because of these facts the automotive industry started to think about another solution. Hybrid drive trains use an electric engine in combination with a combustion engine to reduce the fuel consumption and consequently the CO_2 emission. The technology advances, in the electric development, make the electric power more and more attractive for the General Aviation aircrafts. The limitations about the weight, the electricity storage of batteries and the efficiency of electric engines were improved. In this work, a hybrid drive train for a general aviation aircraft is discussed.

2. Hybrid Concept for a Light Aircraft

This concept is based on replacing the combustion engine of an airplane by a hybrid system consisting of a combustion engine and an electric engine, which has its optimal effectivity to performance ratio at the performance that is needed permanently for cruising flight. That means the electric engine is only used for the take-off, climb or in emergency situations and the combustion engine works the whole time in its optimal performance and efficiency range. The result of this is a reduction of fuel consumption and CO_2 emission.

A general issue in aviation is the weight of the airplane. To keep the payload, a new drive train with a high energy density is needed, which should be at least the same compared to the conventional engine. The first step is to analyse the energy budget. Fig. 1 and Fig. 2 show typical flight profiles for pattern circuits and cruising flight, the required power and phases when support of the electric engine is needed or when electric energy may be recuperated.



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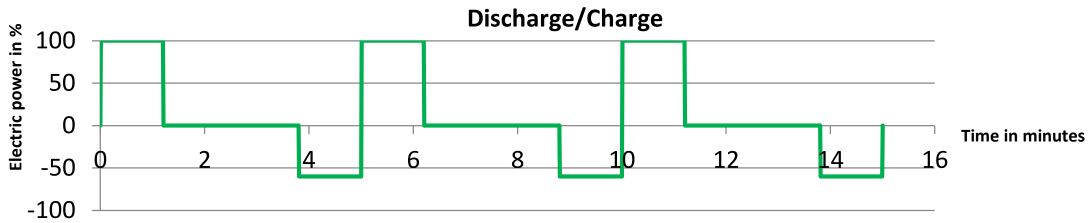

Fig. 1 **Typical flight profile for pattern circuit. a) altitude. b) required power. c) electric power of hybrid system**

a) b) c)

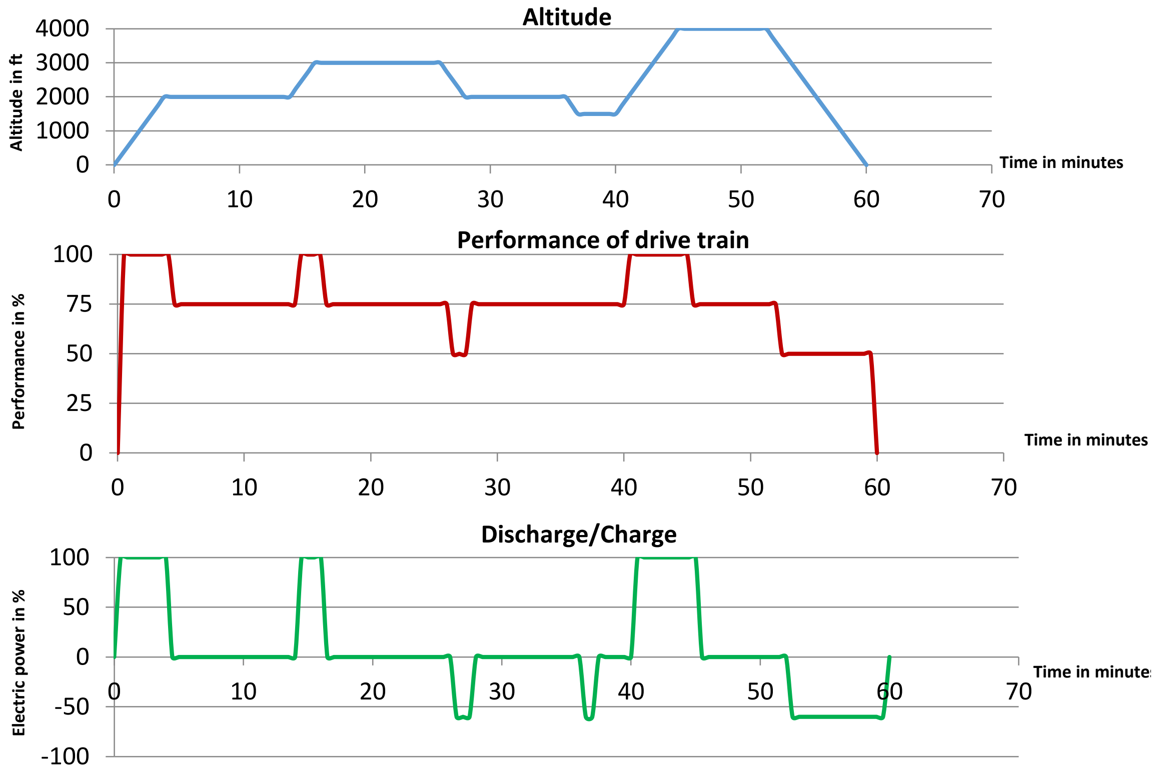

Fig. 2 **Typical flight profile for cruising flight. a) altitude. b) required power. c) electric power of hybrid system**

Peak system power is only necessary for take-off and initial climb. Most time of the flight the continuous power setting is usually between 65% and 75% of maximum power. When the plane descents, the battery can be recharged by keeping the combustion engine in a power setting of best efficiency and by recuperation, because in this phase of flight a very low power setting or even braking power is required. In this way, an excess of potential energy of the aircraft not used for a descent glide can be recycled. The potential energy is calculated by $E_{Pot} = m \cdot g \cdot h$, with aircraft mass m, altitude h and gravity constant g. Compared to automotive hybrid concepts, this is a worthwhile source of energy to recuperate.

Parallel hybrid Setup

In the parallel hybrid concept the electric engine and the combustion engine work on the same shaft. A battery is used to store energy for the electric engine. Fig. 3 depicts the details of this configuration. This drive train enables different kinds of travel modes. The first one is the conventional drive mode with the combustion engine as power source. In the second mode, the "boost" mode, the combustion engine and the electric engine work together for peak system power. The third mode applies when the required power of the aircraft is lower than the power of the combustion engine or even negative in steep descents. In this mode, the battery is recharged by using the electric engine as a generator. For comparison, in the automotive industry the battery is charged during the braking process using the kinetic energy. The kinetic energy is calculated by $E_{Kin} = \frac{1}{2} \cdot m \cdot v^2$, with the car mass m and the speed v. For example, a car with mass of m = 1500 kg, and a speed of v = 27,78 $\frac{m}{s}$ stores a kinetic energy of $E_{Kin} = 0{,}16\ kWh$. Compared to this, an aircraft with the same mass and an altitude of h = 600 m has a potential energy of $E_{Pot} = 2{,}45\ kW$h, which is obviously much more worth to recuperate.

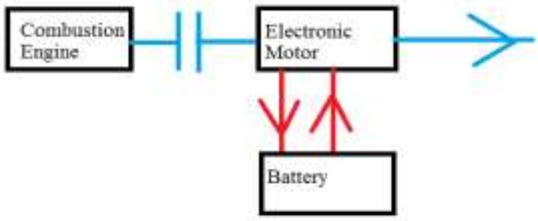

Fig. 3 **Schema of parallel hybrid setup. Mechanical drive (blue) and electrical flow (red).**

3. Example

This concept is based on the airplane *Cessna F172M* [1] with the intention to reduce fuel consumption while keeping the flight performance.

Replacement of combustion engine

The original combustion engine (Lycoming O-320-E2D [2]) will be replaced by a combustion engine with 100 hp (Rotax 914 F [3]) for continuous power combined with an electric engine with additional 50 hp for peak system power as required for take-off, climb and in emergency situations. Tab. 1 shows differences in technical data of both combustion engine types, especially performance and weight.

By replacing the combustion engine, the weight decreases by 46 kg (= 122 kg – 76 kg). This yields a fuel consumption difference at continuous performance power setting of 13.3 l/h (= 33.3 l/h – 20 l/h).

Table 1

Comparison of original (Lycoming) and replacement (Rotax) combustion engine

Engine	**Lycoming O-320-E2D**	**Rotax 914 F**
Rated performance	110.3 kW (150 hp)	84.5 kW (115 hp)
Rated speed	2700 rpm	2387 rpm
Continues performance	71,3 kW (97 hp)	66,9 kW (91 hp)
Continues speed	2350 rpm	2058 rpm
Fuel consumption	33.3 l/h	20 l/h
Weight	122 kg	76 kg

For Lycoming, weight includes carburettor, magnetos, spark plugs, ignition harness, inter cylinder baffles, tachometer drive, starter and alternator. For Rotax, weight includes propeller with speed reduction unit, exhaust system, engine suspension frame, overload clutch, external alternator, air guide hood

As Tab. 1 shows, the performance of the Rotax engine is sufficient for the cruising flight, which is approx. 75% of maximum power of the Lycoming engine (84.5 kW vs. 110.3 kW), lacking a peak power performance difference of 25.8 kW (110.3 kW – 84.5 kW).

Electric engine

To fulfil this peak power performance gap, the hybrid drive train is completed by an electric engine, which delivers the power difference between the Rotax and the Lycoming engine. The comparison above shows that the rated performance difference is approximately 25.8 kW.

The propeller should not be changed by this concept, so it is necessary to calculate the torque difference of both combustion engines to define the electric engine:

$$M_{Lycoming} = \frac{P}{2\pi \cdot n} = \frac{110.3 \cdot 10^3 W \cdot 60}{2\pi \cdot 2700\text{rpm}} = 390.1\ \text{Nm}$$

$$M_{Rotax} = \frac{P}{2\pi \cdot n} = \frac{84.5 \cdot 10^3 W \cdot 60}{2\pi \cdot 2387\text{rpm}} = 338\ \text{Nm}$$

$$M_{difference} = M_{Lycoming} - M_{Rotax} = 52.1\ \text{Nm}$$

As a result, the electric engine needs a torque about approximately 52 Nm and a performance about 26 kW.

Electric engine: Nova 30/50/4 P50

In this work, the electric engine *Nova 30/50/4* P50 was chosen, which is shown in fig. 4 left. This engine is produced by the company *Plettenberg Elektromotoren GmbH & Co. KG.* Its maximum performance is approximately 25.7 kW with a torque about 62.25 Nm by an electric input of 140 Volt and 220 Ampere. Fig. 4 right shows that at a current of 185A the electric engine has approximately a torque of about 52 Nm, a performance about 22.3 kW, a rotational by about 4102 rpm and works with an efficiency of nearly 86.53 %. In tab. 2, the key performance data for a power setting of 52 Nm at 22.3 kW is summarized. The electric Power P_{el} and the required Voltage U are calculated as

$$P_{el} = \frac{P}{\eta} = \frac{22.3\ kW}{0.8653} = 25.77\ kW \text{ and } U = \frac{P}{I} = \frac{25771\ W}{185\ A} = 139.3\ V.$$

a) 

b) 

Figure 4 **a) electric engine. b) datasheet. [4].**

Table. 2

Summary of the reference values of the electric engine at 52 Nm.

Nova 30/50/4 P50 at 52 Nm	
Voltage U	139.3V
Current I	185A
Performance P	22.3kW
Efficiency η	86.53 %
Electric power P_{el}	25.77kW
Rotation n	4120 rpm
Weight m	6.5 kg

Battery dimensioning

As described above, the electric engine needs a voltage of 140 V and a continuous current of 185 A. The electric engine needs the power from the battery in special situations for example take-off, climb or emergency situations. The *Cessna F172 M* has a rate of climb of approximately 500ft/min. With the following equation it is possible to determine a rough guess for the time that the plane needs to climb to the desired altitude:

$$Time = \frac{Altitude}{Rate\ of\ climb}$$

For the calculation of the battery size respectively the capacity, the required time for the three situations within one flight and a safety factor are taken

$$C = (T_{TO} + T_C + T_E) \cdot x_S \cdot I$$

with the capacity C, the take-off time T_{TO}, the climb time T_C, the estimated emergency situation time T_E, the safety factor x_s and the electric current I.

For the following calculation the reserve for the emergency situation is set to T_E=10 min. The safety factor is for the battery that there is every time enough capacity because the senescence or another failure. The safety factor amounts 20 %.

$$C = (0.008h + 0.075h + 0.166h) \cdot 1.2 \cdot 185A = 55.278Ah$$

As a result, the drive train needs a rechargeable battery with a minimum capacity about 55 Ah, a current of 185 A and a voltage of 140 V. For the electrical storage in this hybrid drive trains the best battery type is the lithium-ion technology [5].

Battery: VLE 11-84

In fact of the previous calculation, the battery cell *VLE 11-84* [6] was chosen. This accumulator is produced by the *Saft Batterien GmbH*. This battery has a higher capacity than the drive train needs and a higher continuous current. With this battery a better performance is achieved and a better torque is reached than calculated at the beginning. The datasheet shows that the electric engine has at a current of about 200 A, a performance of 23.7 kW and a torque with 56.3 Nm. When the drive train uses the battery with the *Nova* engine at 185 A, then it has enough capacity for 27.24 minutes.

$$t = \frac{C}{I} = \frac{84\text{ Ah}}{185\text{ A}} = 0.454\text{ h} = 27.24\text{ min}$$

The electric engine needs a voltage of 140 Volt. In a series connection, the voltages of cells are added.

$$number\ of\ cells = \frac{U_{ges}}{U_{cell}} = \frac{140\ V}{10.8\ V} = 12.96$$

As a result, 13 cells of the *VLE 11-84* are needed connected in series to achieve a voltage of 140.4 Volt. The mass of 13 cells is 104 kg.

Power electronics

The drive train needs power electronics which can deal with the rated and maximum power from the battery and the electric engine. The "*Motorsteuerung MST-140-200 V3"* [7] with a weight of 2 kg is a good choice, because this power control unit is adapted for the *Nova 30/50/4 P50* and is also produced by *Plettenberg Elektromotoren GmbH & Co. KG*.

Weight calculations

To benchmark the hybrid concept, the weight of the new configuration is compared with the weight of the old configuration:

Table. 3

Comparison of the new and old configuration

component	old configuration	new configuration
combustion engine	122 kg	76 kg
electric engine	----	7 kg
battery	----	104 kg
power electronic	----	2 kg
empty weight	620 kg	686 kg
Δ_{weight}	66 kg	

The payload is calculated as $m_{PL} = m_{TO} - m_E = 1043 \text{ kg} - 686 \text{ kg} = 357 \text{ kg}$, with the maximal take-off weight m_{TO}, an empty weight m_E and the payload m_{PL}. Fig. 5 shows the fuel load and the flight time as in function of the payload.

4. Conclusion and Outlook

With today´s development, it is possible to design a hybrid drive train in a general aviation aircraft. Although that on the one hand the new configuration has a higher weight and a negligible lesser performance, there are much more benefits on the other side.

Fig. 5 **Payload function**

Figure 5 shows that the new drive train can hypothetical fly over 7.2 hours in comparison to the old one with a flight time of 4.2 hours [9]. Another benefit is that the new combustion engine is turbocharged. That means that the performance is independent from the altitude respectively the air density. The electric engine performance is also independent from the air density. As a result of this, there is a much better performance in low air density areas than with the old drive train.

With this new drive train it is also possible to design a new front of the airplane because the new smaller engine and in fact of the water cooling system of the *Rotax* engine, it doesn't need large air intakes in the chassis. A comparison between the front of the *Cessna* and the front of a *Katana* [8], which contains the *Rotax* engine, shows the aerodynamic benefits of the design.

In this paper the electric energy storage is a lithium-ion battery. Future work may deal with other solutions, for example a fuel cell [10] or ionic liquid [11].

With the advance in the electronic development, the density of batteries and the energy density of electric engines will get better and better. That means that there will be more opportunities available with the hybrid drive train in the general aviation. The example was a small aircraft. But today and in the future with the development of the electronic, the hybrid drive train may be more and more attractive for the commercial airlines [12].

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