DIMONA – the First Serial Hybrid Aircraft.

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Summary

As the first serial hybrid aircraft, the motor glider Dimona E-Star equipped with a Wankel motor plus generator, an electric drive and an accumulator system performed its 40 minutes maiden flight in spring 2011. The paper elaborates on goals and advantages of the technology chosen and describes the overall system, the drive train consisting of electrical and combustion components and the electrical accumulators. Special emphasis is laid on appropriate system values, connections and control as well as on electrical and physical characteristics.

1 Introduction

The fact, that aircraft are responsible for about 2% of the overall CO₂ emissions gives rise to intensive efforts to reduce fuel consumption. A further emission, i.e. noise, is the source of increasing annoyance of residents around airports and requires therefore massive counter-actions.

As a first step in this direction, at the Paris Air Show in Le Bourget in spring 2011, EADS, Siemens AG and Diamond Aircraft demonstrated the world's first aircraft with a serial hybrid electric drive by a 40 min. flight of the motor glider Dimona E-Star (Diamond HK36 - Fig. 1). During tests, even more than two hours flight time could be attained.

The development is expected to pave the way towards the electric flight as a general means of transportation.

2 Objectives / Benefits

The development goals of the technology demonstration were:

- To basically evaluate electrical power technologies for aircraft propulsion systems,
- To develop design fundamentals and skills w.r.t. high performance batteries and light weight electrical drives as well as the pertinent lab facilities,
- To generally explore the potential opportunities for the all-electric aircraft and to provide the related data base and fundament and finally:
- To pave the way for a later use also in large-scale aircraft.
As major advantages of the technology there are expected:

- A general reduction of fuel consumption and emissions as well as
- Silent take-off and emission free ground operations.

3 The Consortium

The consortium consisted of the partners Siemens, Diamond Aircraft and EADS-IW. The work share between the partners was as follows:

- Diamond Aircraft provided:
  - the carrier,
  - all necessary integration work,
  - the flight testing and
  - by its subsidiary, Austro Engine, the combustion engine.
- Siemens supplied the electric drive train consisting of:
  - electrical motor,
  - electrical generator,
  - the inverter assembly for e-motor and e-generator for adequate conversion of electric energy in the drive system,
  - drive controller and
  - the interfacing to the existing shaft.
- EADS-IW contributed:
  - the battery and
  - the pertinent management and protection system.

4 The Overall System.

The propeller of the aircraft was driven by a 70kW electric Siemens motor powered by a Wankel engine from Austro Engine through a Siemens generator. The Akku Pack from EADS-IW served as booster, e.g. for climb flight. With a cooling system it will be reloadable during cruise.

In detail, the serial hybrid aircraft architecture consisted of:

- A Wankel combustion engine (Fig. 5),
- A permanent magnet synchronous e-generator,
- A permanent magnet synchronous e-motor (Fig. 6 to Fig. 8),
- An electronic inverter for e-generator and e-motor,
- A drive controller system,
- A high voltage, high power LiFePo battery (Fig. 12) including a safe and reliable, dual redundant cell pack technology (Fig. 10) and
- A comprehensive battery protection and management system.

The electric drive was integrated in front of the combustion motor (Fig. 2 and Fig. 3)
5 The Carrier

The carrier was a Diamond HK36 (Fig. 1), the nose (Fig. 3) and wing (Fig. 4) of which provided the space requested for the electric drive and accumulation system.

The HK36 Super Dimona is a low-wing, T-tailed, two-seat motor glider produced by Diamond Aircraft Industries with the main system data:

- Capacity: one pilot and one passenger,
- Span: 16.0 m,
- Wing area: 15.24 m$^2$,
- Aspect ratio: 16.8,
- Airfoil: Wortmann FX 63-137,
- Empty weight: 497 kg,
- Gross weight: 770 kg,
- Fuel capacity: 80 litres

Performance:

- Cruise speed: 182 km/h (98 kt),
- Never exceed speed: 275 km/h, (148 kt) sea level to 6000 feet,
- Range: 1094 km,
- Maximum glide ratio: 27:1 at 105 km/h,
- Rate of sink: 0.91 m/s (179 ft/min) at 79 km/h,
- Wing loading: 48.56 kg/m$^2$

6 The Combustion Drive

The combustion motor (Fig. 5) is a Wankel motor from the Diamond subsidiary Austro Engines. It represents the first element of the serial hybrid electric drive, a technology known from automotive industry.

The fuel consumption is low, since the motor is running steadily at the low level of about 30 kW to drive the generator and through a Siemens inverter the propeller.

The electric drive train (Fig. 6) consists of the electric generator, the electric motor and their power electronics, including a control system for power management and distribution functions. The electric drive is
mounted ahead of the combustion motor. Fig. 6 shows the assembly of the components without cooling system.

![Fig. 6 Electric drive installation](image)

An additional connection box, installed behind the Pilot inside the cockpit, connects the two battery packs in the wings (see chapter 9) and performs insulation monitoring of the high voltage DC link.

![Fig. 7 The electric machine](image)

The inverter with liquid cooling is designed to meet IP54 requirements. The operational voltage is 400V up to 840 V with a maximum allowable DC link voltage of 1100V.

Both the electric motor and the electric generator are based on the same electric machine (Fig. 7). The continuous power of 30 kW and maximum power of 70 kW is suitable for the aircraft propulsion as well as for power generation.

The electric machines are liquid cooled (see chapter 8). Temperature monitoring and PTC triplets prevent the stator coils from overheating. The electric machine is designed for operation altitudes up to 3600 m MSL and ambient temperatures of -10° to 38°C.

In order to drive the propeller with the correct speed, the electric motor is connected to a gearbox (i=2.84). This provides two advantages: the higher speeds of the electric motor reduce its dimensions and weight and the loads of the propeller do not have to be considered in the mechanical design of the electric motor.

### 8 Cooling

Fig. 8 shows the electric motor including cooler (below the electric drive) and different cooling tubes.

![Fig. 8 The electric drive and cooling system](image)

Water/glycol (50/50%) cooling fluid is used for electrical machines and inverters. The combustion engine has its own liquid cooling system.
9 Energy Accumulation

The electric energy is stored in LiFePo cells of 2.3 Ah (Fig. 9) assembled by EADS-IW.

![Fig. 9 The cells](image)

Each battery consists of 6 cell modules and 1 control module.

![Fig. 10 Schematic view of cell arrangement](image)

Each wing featured 216 devices in serial, each device consisting of 2 parallel connected cells. The cell weight was 70g leading to a weight of 2 wing accus of 105kg, cooling and cell connection not included.

Each wing accu had an output power of 35kW.

The accus provide additional power particularly during start and climb, but can also be applied as booster during high power manoeuvres. During cruise, a recharging of the accumulators is foreseen. Their energy is transferred by the aforementioned Siemens-developed inverter to the propeller.

In order to enable the battery integration in the aircraft’s wing nose, the cells had to be grouped and connected in an appropriate way (Fig. 10 and Fig. 11).

![Fig. 11 Cells assembled for integration](image)

The battery design was driven mainly by the available space in the wings and by the demonstration requirement of a full power battery operation duration of at least 3 minutes. The arrangement of the cells was optimised to accomplish a very small and flexible device.

At the demonstration flight, no cooling was available, however the design allowed one complete discharge without cooling, if the ambient temperature was in the range of 10 to 35°C.

Meanwhile, a forced air cooling system has been developed. A 60 W fan is needed to overcome the pressure drop of the air flow in the wing.
The entire battery system is shown in Fig. 12.

In order to enable the battery assembly in the aircraft’s wing nose, the appropriate space had to be foreseen (Fig. 13 and Fig. 14). The battery length corresponds roughly to the half span outside the fuselage and is fitted into the wing from its tip (Fig. 15).

The typical behaviour during discharge at the laboratory (without cooling) at resistive load is described for the voltage in Fig. 16 and for the power in Fig. 17.
The temperature rise during discharge is depicted in Fig. 18.

Fig. 18 Temperature increase during discharge

The cells were charged at 778 V by a current of 10 A.

Each pair of cells was monitored. The monitor electronics cut the power line to the respective accu, if at least one cell voltage value exceeded or fell short of prescribed levels, or if the temperature was higher than the respective limit. Each wing accu had an independent power control unit. Hence, if one accu switched off, still the second remained operational.

Fig. 19 describes the discharging of the battery cells vs. time during a full power climb test flight. The battery was discharged during 2.6 minutes. The temperature rate was 7.7 K/min compared to 8 K/min in the laboratory, the latter value being measured without harness and connection elements.

Fig. 19 Discharging of battery cells vs. time during a full power climb flight

10 Conclusions and Outlook

By its maiden flight of more than 40 minutes, the world’s first serial hybrid aircraft has pushed the door open to the technology of general electric flight.

It has shown also, that already for the hybrid flight, a silent take-off and emission free ground operations have become possible.

As a next step, drive train and energy accumulation will be optimised, e. g. by increasing the efficiency of electric motor and batteries. This will pave the way towards hybrid aircraft configurations ready for the market, expected to be an intermediate step on the way to the all-electric aircraft.