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e-DEAL engine for a Mach 0-Mach 5 cruiser

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Abstract

During the 2000th, MBDA France was developing a large scale engine aiming at demonstrating the ability of a Continuous Detonation Wave Chamber (CDWC) to be integrated to a turbofan to provide up to 15% more fuel efficiency. Nevertheless, harnessing mechanical power from supersonic flows exiting CDWC without substantial aerodynamic losses is very challenging.

In that view, MBDA developed with Von Karman Institute and Purdue University a Wavy Bladeless Turbine concept allowing reducing speed of supersonic flow while extracting substantial mechanical energy from it. By another way, MBDA France, in cooperation with the French SME FranceCol, prepared a first demonstration of a turbineless propulsion system using electrical air compression.

Taking benefit of this background, the concept of an **e**lectrically assisted **DE**tonation wave **A**ir breathing **L**iquid fuel engine (e-DEAL) able to power a Mach 5 cruiser is proposed. After a detailed description of e-DEAL concept operation, a possible flight demonstration using a small dedicated vehicle is proposed.

Keywords: *Detonation Wave Engine, Hybrid Propulsion, Hypersonic Air breathing Propulsion*

Nomenclature

e-DEAL – electrically Assisted DEtonation wave Air breathing Liquid fuel engine

CDWE – Continuous Detonation Wave Engine (called also Rotating Detonation Engine)

CDWChamber – Continuous Detonation Wave Chamber (where detonation wave(s) occurs)

1. Introduction

1.1. Back-ground on CDWE

Due to its thermodynamic cycle, the Continuous Detonation Wave Engine has theoretically a higher performance than classical iso-pressure propulsion concepts. CDWE can also be considered to reduce the environmental conditions generated by other detonation engines such as PDE while reducing the importance of initiation issue and simplifying some integration aspects.

Since 2002, MBDA France has been cooperating with LIH in Novossibirsk (Russia), CNRS-ICARE Institute in Orleans (France) and CNRS-Pprime Institute in Poitiers (France) to better understand CDWE operation and address some key issues for an actual use as part of a propulsion system.

On the basis of these studies, and considering the growing interest shown around the world for this concept, a subscale demonstration engine was designed and manufactured in 2011 with the support of the Airbus Group (Fig 1). This small demo aimed, in a first step, at replicating experimental works performed at LIH and in a second step, it allowed extending the test duration and testing the ability to detonate of H_2/CH_4 mixtures ([1] to [7]).

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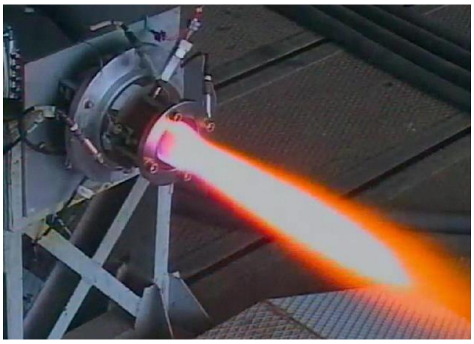


Fig 1. H2-air and H2/CH4-air small scale CDWE engine on test on MBDA test line

MBDA France is the owner of several patents related to CDWE ([8] to [10]) and with support from European FEDER funds and from Airbus Group Nursery, MBDA France developed a large scale engine (Fig 2) aiming at demonstrating the ability of a CDWE to be integrated to a turbofan engine using Liquid HydroCarbon (LHC) fuel for which the fuel consumption, then CO2 emission, could be reduced by 15%. ([11]).

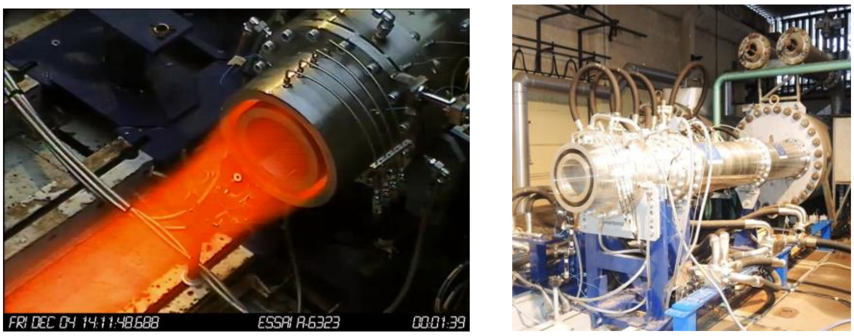


Fig 2. H2-air and H2/LHC-air large scale CDWE engine on test on MBDA test line

Nevertheless, harnessing mechanical power from hot supersonic flow exiting CDWC is very challenging. MBDA France developed with Von Karman Institute and Purdue University its patented Wavy Bladeless Turbine concept turbines, which is a viable alternative to extract power in such harsh conditions without restricting the operating conditions. Moreover, such a concept allows reducing speed and total temperature of supersonic flow while extracting substantial mechanical energy from it without important aerodynamic losses. Drastically limiting such losses being key to actually take benefit from the gain in thermodynamic cycle, particularly from total pressure increase provided by detonation process [12]).

After a detailed preliminary study based on numerical simulation and associated design optimization tool leading to the concept of wavy bladeless turbine (Fig 3), MBDA and Purdue University performed an extensive experimental work (testing in 2D cascade configuration) (Fig 4) to better understand how such a bladeless turbine can be optimized over a large range of operating conditions ([13] to [20]).

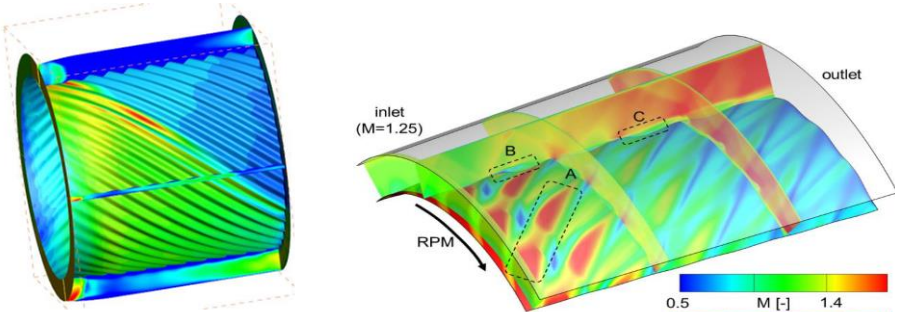


Fig 3. Numerical simulation of a wavy bladeless turbine

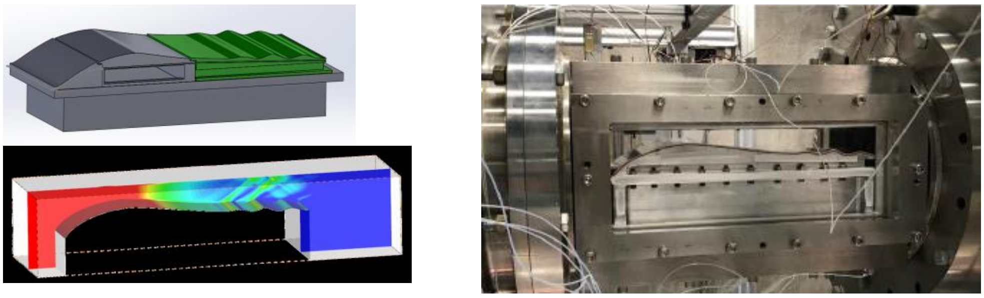


Fig 4. Experimental work in progress at Purdue University

1.2. Back-ground on hybrid propulsion

By another way, the recent progress on high performance batteries (high power density AND high energy density) and high performance electric motors and associated power electronics could enlarge the design space for aeronautical propulsion systems. Specifically, using an electrically powered compressor could dramatically reduce constraints on turbine, or lead to suppress the turbine, opening the way for taking full benefit of new propulsion concepts.

MBDA, in cooperation with the French SME FranceCol, prepared a first demonstration of a turbineless propulsion system using electrical air compression (Fig 5) which can provide some new possibilities for the compressor design as multi-counter-rotating-stage compressor, particularly promising when trying to provide the well adapted compression level in a very large range of flight Mach number.

Using counter-rotating stages for the compressor avoids the need of stator between rotors. Then, in absence of classical turbine stages (but possibly with a bladeless turbine) engine integration is sensibly simplified as the external casing of the engine is a simple cylindrical part in which one can place an already fully integrated rotating sub-assembly. By another way, the rotor of the electrical motor is the internal shroud of the compressor and then a lot of mass can be saved as shown on Fig 6.

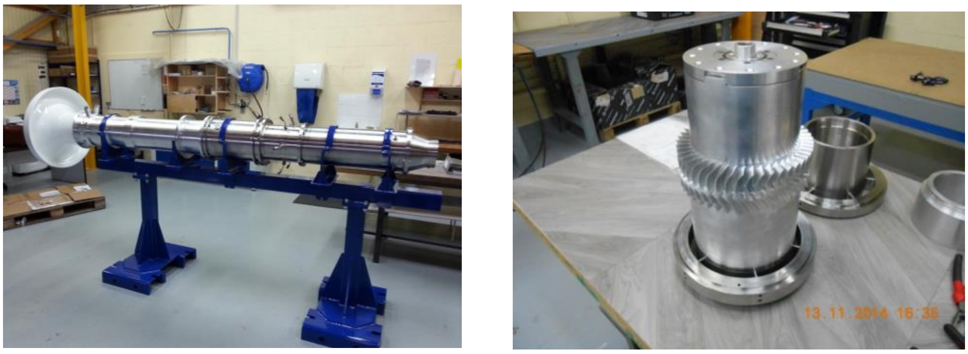


Fig 5. Hybrid air breathing propulsion – 200mm diameter preliminary demo and its 2 counter-rotating stages compressor

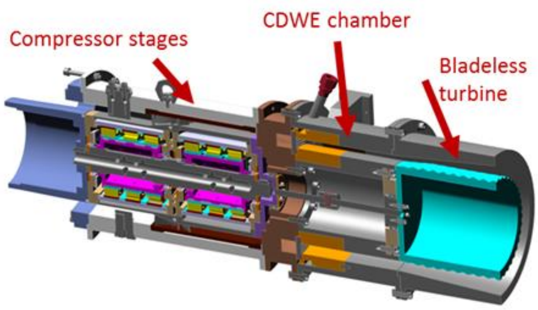


Fig 6. Final hybrid Demo configuration (at that stage, only aerodynamic tests were performed)

2. e.DEAL engine concept

Based on this technology back-ground, an **e**lectrically assisted **DE**tonation wave **A**ir breathing **L**iquid fuel engine (e-DEAL) is proposed to power a Mach 5 cruiser.

The e-DEAL engine is essentially a LHC fueled ramjet with low Mach electrically assisted compression able to power a vehicle from Mach 0 to Mach 5 taking full benefit of CDW process (fuel consumption, low emission, maximum specific thrust) while avoiding limitation provided by a classical turbine:

- At low Mach number, two electrically driven counter-rotating compressors are working in tandem to provide enough compression before entering the CDWChamber ("full electric compression mode" on Fig 7).
- Then, when the Mach number is enough high to ensure a minimum ram compression, one of the two compressors is by-passed ("reduced electric compression mode" on Fig 7).
- Finally, as soon as the ram compression is enough important to provide the right pressure at the entrance of the CDWChamber, the second compressor is also by-passed and the engine becomes a pure CDW ramjet engine ("ramjet mode" on Fig 7).

Following the LHC fueled CDWChamber concept patented by MBDA France ([9]), the CDWChamber is preferably made of high temperature composite material cooled by the fuel. Thanks to this, the liquid fuel, while cooling the engine walls, is pre-vaporized to enhance its ability to detonate.

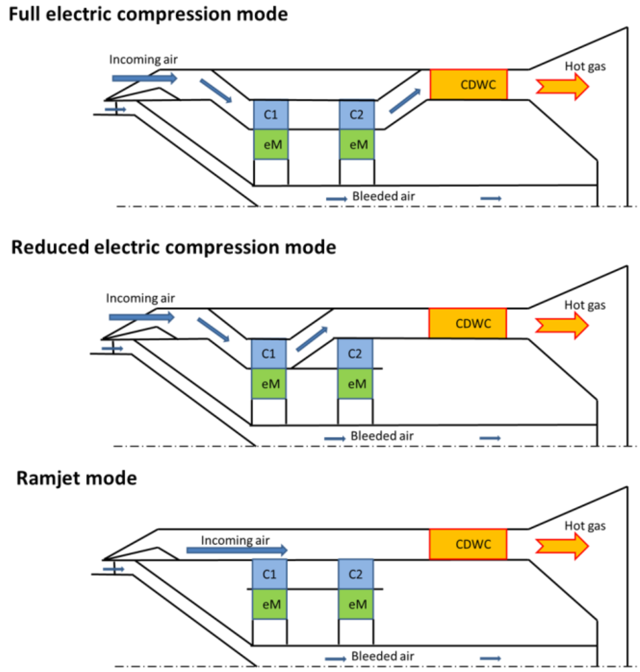


Fig 7. e-DEAL engine concept and operation modes (2D cut of the axisymmetric system)

Depending of the vehicle to power and the corresponding mission, a bladeless turbine can be added at the exit of the CDWChamber to extract some electric power from the flow. In principle, a classical turbine could be also added downstream the bladeless turbine, transforming the engine in a CDW turbojet with electrical power transfer from turbine system to compressor system. But such a system would be very demanding in terms of electrical link between turbine and compressor. It would be preferable to combine a rechargeable battery and a bladeless turbine to cover the electrical needs of compressor: the turbine contributing with battery in powering compressors at low Mach number and recharging battery in ramjet mode. During the descent phase, it could be also possible to use electrical motors driving compressors as electrical generators when operating in windmill mode.

3. Possible flight demonstration

As described here above, a lot of enabling technologies have been already addressed but need to be further matured. In that view, a flight demonstration program could be developed to demonstrate the feasibility of the e-DEAL engine concept and actually assess reachable performances. A preliminary design study for a possible flight demonstrator has been performed to define the minimum option allowing to demonstrate the concept while limiting as much as possible related costs and risks (Fig 8).

The proposed demonstrator is a small vehicle, rail launched with a booster accelerating the system up to ~Mach 0.6. From that point, the vehicle autonomously accelerates up to Mach 5 then cruises in pure CDW ramjet mode. At the end of the cruise phase, the vehicle decelerates through a gliding phase up to Mach 0.6 when the propulsion is re-ignited for final landing. After battery recharging and refueling, the vehicle is again ready for a new flight. Considering targeted maximum Mach number, the vehicle and its propulsion system should be reusable for a few missions.

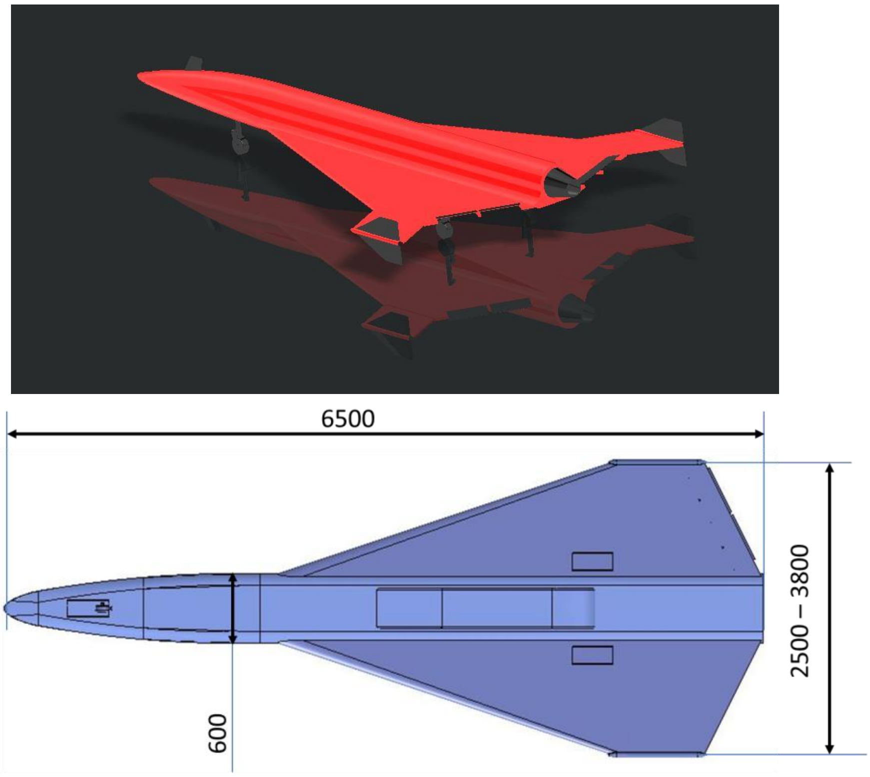


Fig 8. Flight demonstrator for re-usable e-DEAL engine operating from Mach 0 to Mach 5

The choice of a rail launch and the use of a booster allows reducing the size of the vehicle and using a simply extractible landing gear, all these elements leading to a dramatic limitation of the cost.

In the same way, extractible wings extension allows providing the right aerodynamic configuration at high Mach number while providing enough lift for landing while avoiding a more complex retractable system for wings extension (Fig 9).

However, the thrust available at very low Mach is sufficient to perform a flight specifically dedicated to the demonstration of autonomous take-off and landing:

- self acceleration on runway (landing gear and wings extension already extracted)
- take-off at about 250 km/h
- short flight at about Mach 0.6 (landing gear remaining outside fuselage)
- landing at about 200 km/h (need of braking system or a rear parachute + braking net)

A movable plug nozzle can be used to maximize the engine performance by adapting the throat along the flight Mach number envelope and to take the best benefit of each operation modes.

As previously discussed, a bladeless turbine could be added at the exit of the CDWChamber to recharge the battery but, in order to limit the risk and cost, the first intent is to rely only on a battery which will be recharged on-ground before each mission.

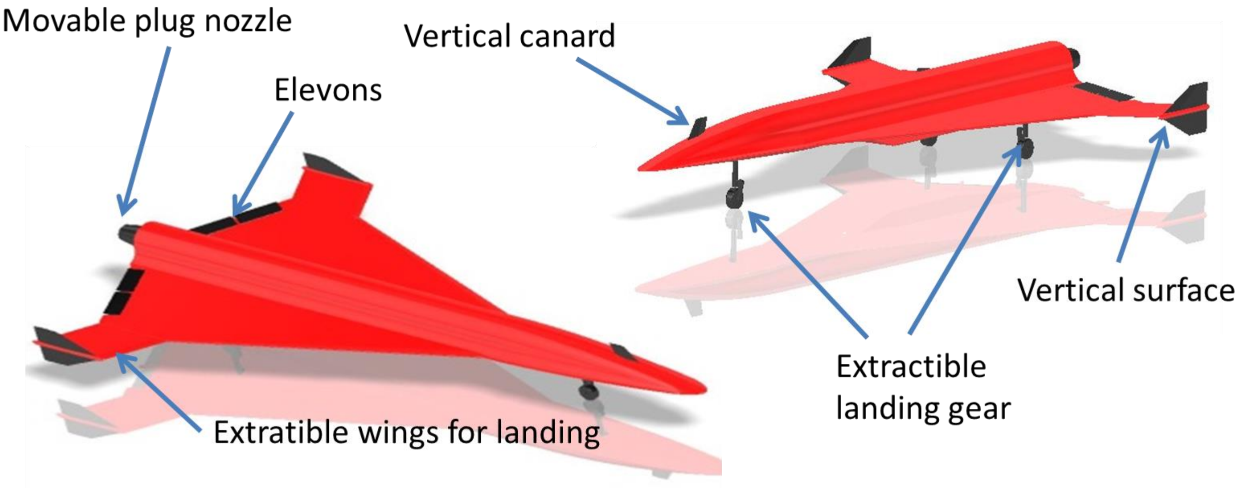


Fig 9. Some features of the flight demonstrator

4. Preliminary design and performances assessment

Some specific points of design have been preliminary addressed as, for example, numerical simulation to determine aerodynamic characteristics of the vehicle as well as related aero-heating (Fig 10) or to design the four counter-rotating stages compressor (Fig 11).

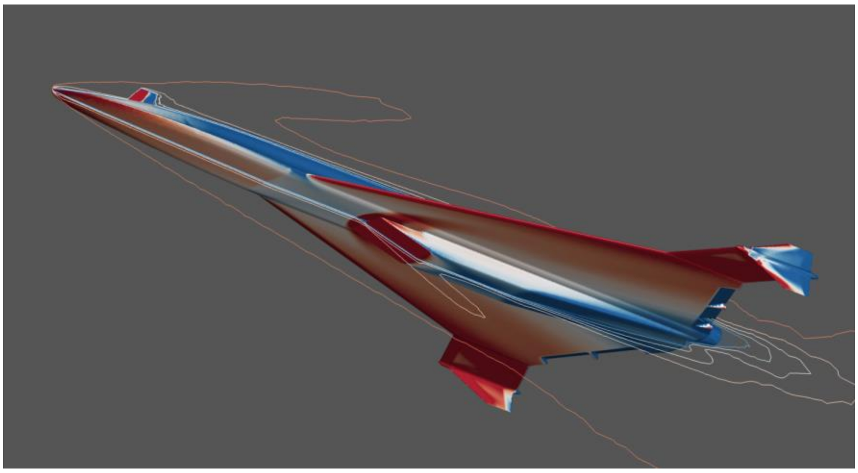
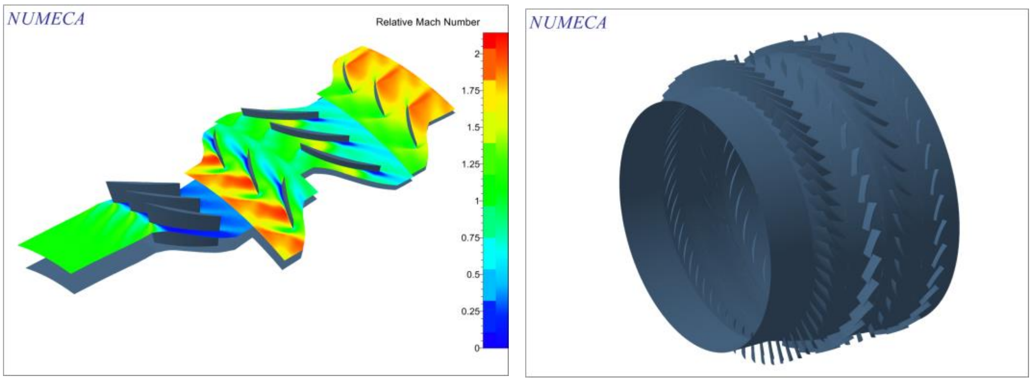


Fig 10. Preliminary study on aero-heating



- Tip diameter ~ 440 mm
- Power ~ 180 kW per rotor
- Rotational speed 18000 rpm
- compression ratio Π = 3.8

Fig 11. e-DEAL engine concept and operation modes

Based on all these elements, a preliminary mass breakdown is given in Table 1.

Table 1. Preliminary mass breakdown

Component	**Mass (kg)**
Main battery	400
Fuel	150
Fuel tank & system	35
Air intake	30
Compressor	140
CDWChamber	40
Nozzle	15
Wings	150
Control surfaces	30
Avionics	35
Instrumentation	25
Landing gear	60
Margin	90
Total vehicle	**1200**
Booster propellant	235
Booster structure	75
Total booster	**310**

Nota bene:
Performance assumption for the main battery are power density 2kW/kg and energy density 150 Wh/kg.
Performance assumption for the electrical motors is 8 kW/kg (power electronics included)

A typical mission profile is defined on Fig 12.

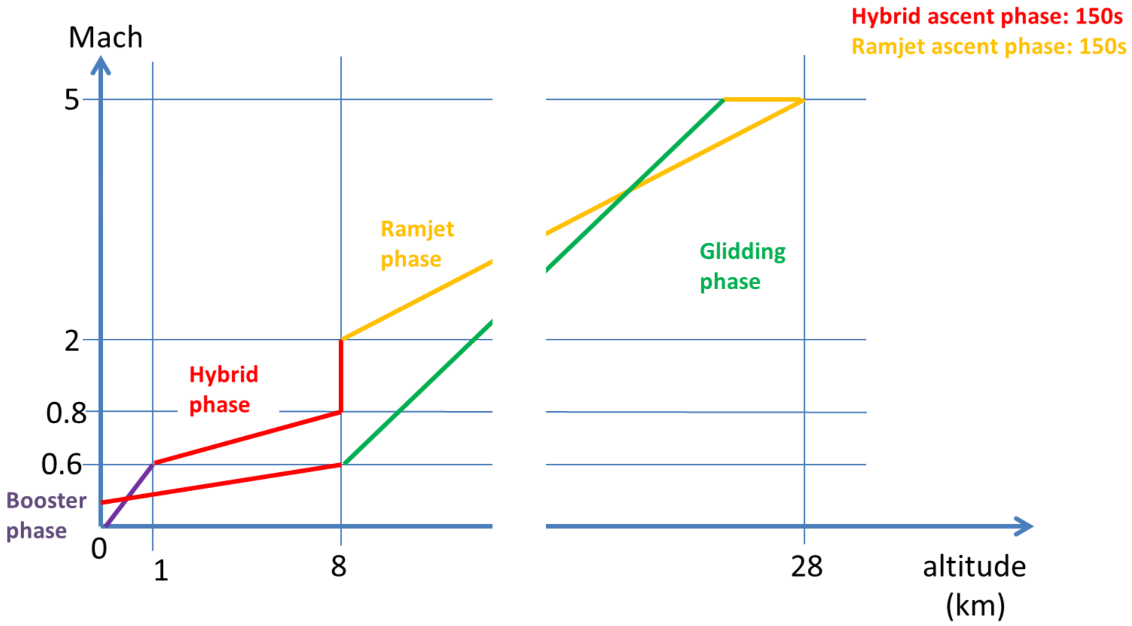


Fig 12. Typical mission profile

On the basis of preliminary design results, an aero-propulsive performance model has been established and some trajectory simulations have been performed. Fig 13 gives main parameters of the ascent phase for a typical mission.

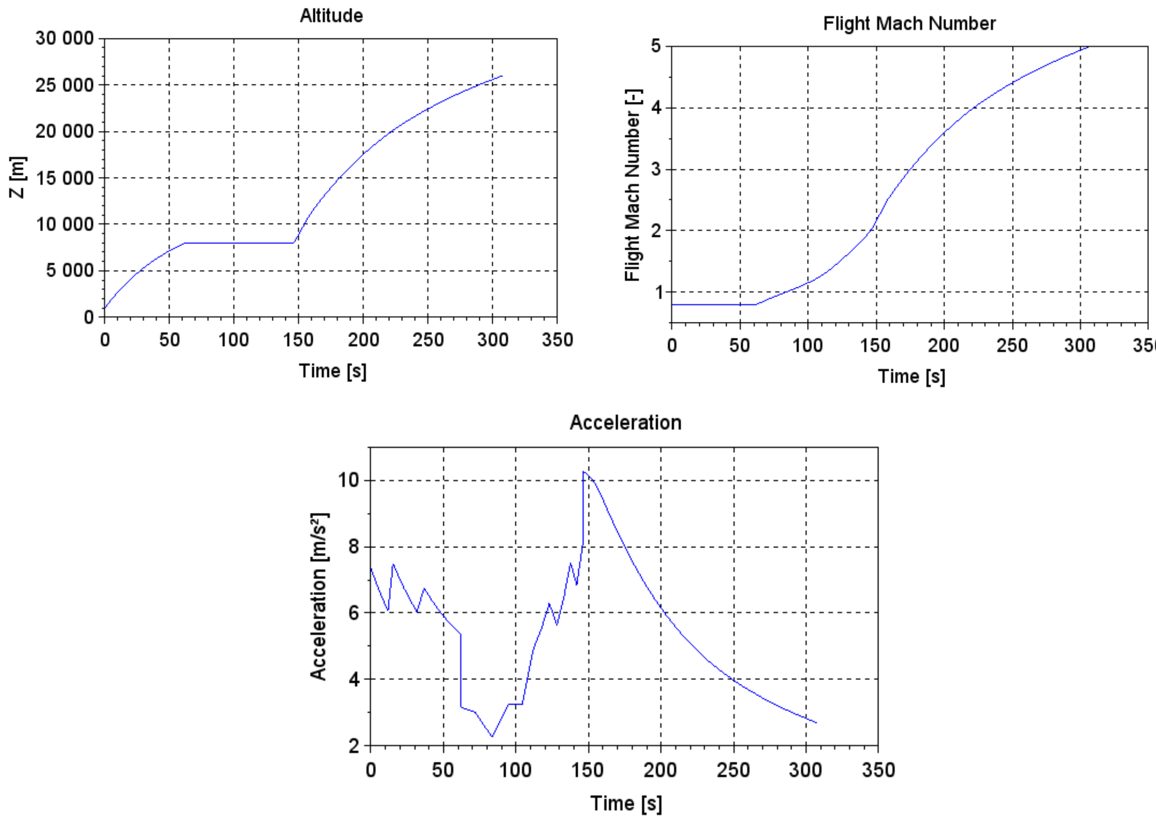


Fig 13. Trajectory simulation results

The system presents some margins. For example, if battery performance is limited:

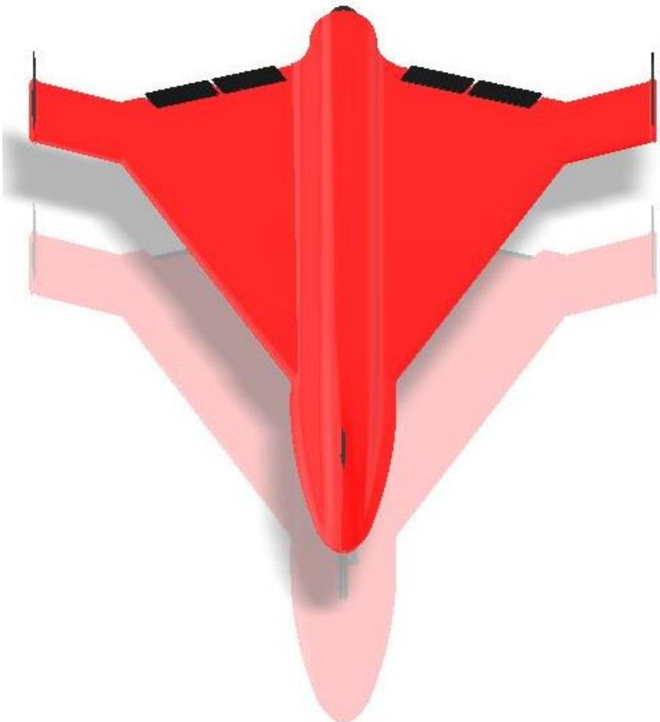
- the total mass can be slightly increased to embark more battery,
- there is a margin on booster which could allow reaching higher Mach number and altitude before starting hybrid phase.

Moreover, batteries technology is permanently improving. Particularly, solid electrolyte technology could help a lot for the considered system for which the battery is sized by the power density more than the energy density.

5. Conclusion

Works undertaken since long time on CDWE and on hybrid propulsion allow proposing an innovative propulsion concept able to power a Mach 5 cruiser. Beyond already existing technology basis, a flight testing program could further demonstrate feasibility and better assess reachable performances.

As a matter of fact, flight testing a small and relatively simple Mach 0 – Mach 5 vehicle would demonstrate a propulsion system able to provide the needed acceleration capabilities all over the Mach number range and would provide a better knowledge and confidence on achievable performances.



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