AFFORDABLE TECHNOLOGICAL DEMONSTRATOR FOR HYPERSONIC FLIGHT[*]

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ABSTRACT
The paper shows the development of a new family of small and affordable technological demonstrator for future reusable launchers. The first encouraging results are here presented and discussed.

1. INTRODUCTION

Nowadays the importance of space activities is increasing and many countries may play a useful role in aerospace research.
We strongly believe that fully reusable launchers will play a key role in the development of future space activities. Up until now this kind of space systems has not been successfully carried out: in fact today only the Space Shuttle, which belongs to the old generation of launchers, is operative and furthermore it is not a fully reusable system. In the nineties many studies regarding advanced transatmospheric planes were started, but no one was accomplished because of the technological problems encountered and the high financial resources required with the corresponding industrial risk.
Nowadays only the Lockheed Venture Star has chances to be carried out, and this will take quite a long time thus the operative life of Space Shuttle will have to be extended for the International Space Station support.
Due to the above-mentioned technical and financial aspects, industrial research activities are focused on designing, building and testing technological demonstrators for future space planes. These are flying vehicles often unmanned, which reproduce in a reduced scale some characteristics of the future operative space planes and are able to explore to some extent the flight envelope.

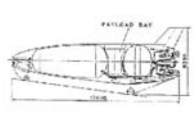
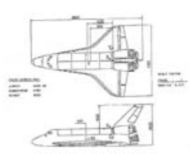
Lockheed X-33 U.S.A. (under development)	It will partially explore the Venture Star flight envelope from take-off to Mach faster than 13, z= 97 km.	Vertical T.O. Gliding descent, horizontal landing	Two liquid rockets: T_{TO}=1860 kN $Mass_{TO}$=123800 kg L=20.4 m, b=20.7 m	
Rockwell X-34 U.S.A.	It will perform sub-orbital flight to M=8, z=75km.	Air-launched from a Lockheed L1011 "Tristar"; unpowered glide back to the ground for a runway landing.	One liquid rocket: T=267 kN $Mass_{launch}$=22426 kg L=17.9m, b=8.5m	
X-38	It flies free for 44 sec and it reaches speeds of over 800 km/h.	The X-38 is released from a B-52 aircraft at an altitude of 11,900 m. At the end of the flight the X-38 deploys a drogue parachute that slows the vehicle down to 113 km/h.	Unpowered W=71 kN L=4.42m, b=4.42m	
HIMES (reduce scaled model) JAPAN-tested	The reduce scaled model of the transatmospheric technology demonstrator reaches z=80 km.	Dropped from a balloon at z=19 km and then it climbs powered by a booster. Gliding descent and horizontal landing.	W=1900 N; $W_{with\ booster}$=4800 N L=13.6m; b=9.3m $V_{balloon}$=15000 m^3.	
FALKE Germany (under development)	Model not powered of Space Shuttle Orbiter to test the descent (it reaches M=1.6) and the recovery phases.	Dropped from a balloon at z=45km and then it descents gliding. Recovery with parachutes.	W=26 kN L=6.02m; b=4.36m $V_{balloon}$=600000 m^3	

Table1: Examples of transatmospheric technological demonstrators

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Table 1 gives some examples of technological demonstrators, already developed or still under way. Technological demonstrators may be very expensive systems and very few countries can afford their development. Universities and countries with limited budgets for space research can focus on more cost-effective demonstrators, which can still be useful to gather information even though they are simpler, smaller and thus more affordable.

2. BASIC CONCEPTS FOR AN AFFORDABLE DEMONSTRATOR

Starting from the previous considerations, the Systems Engineering Group of Aeronautical and Space Engineering Department (DIASp) at Politecnico di Torino has started investigating the feasibility of a technological demonstrator [1].
At the beginning it was considered a plane whose shape and size were similar to the ones of the Falke (see table 1) but unlike the Falke a propulsion system was adopted. We thought that the launch from a balloon could avoid all the problems related to the ascent phase (for instance the waste of propellant in the first phase when air density is high).
Taking into account the lack of available resources (people and money) we focused on stressing the importance of affordability by reducing the size and performances of the demonstrator and by pursuing some quite unusual ideas. Obviously the target was to maintain the benefit to cost ratio value.

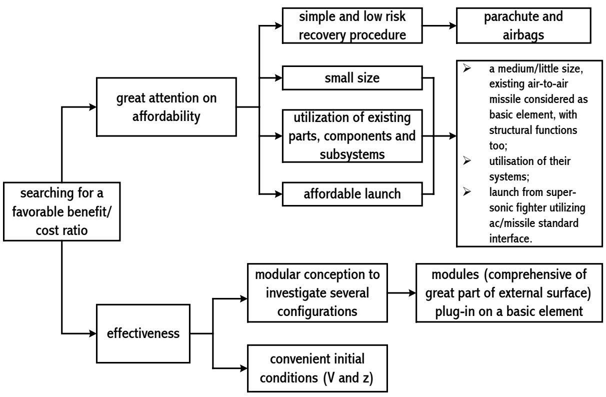

Fig.1: Logical process

Figure 1 sums up the logical process, which led us to the design choices. The achievement of affordability characteristics has been pursued by:

- hypothesizing a simple and low risk recovery procedure as the demonstrator is unmanned. This drove us to the employment of parachute and airbags for landing;
- considering the utilization of existing items. A real air-to-air missile has been chosen as the basic element (figure 2) for the demonstrator. It holds structural functions, in particular bending strength in x-z and x-y planes and torsion strength about the x-axis, and it hosts most onboard systems.
- hypothesizing an affordable launch if a supersonic fighter is considered for launch. In fact there is no need to arrange an aircraft to carry and launch the demonstrator if the fighter and its standard missile will be used. Thanks to the small size and reduced weight of our demonstrator this system for launch is possible, while for the X-34 an arrangement of a L1011 transport plane was necessary. An alternative solution is represented by the launch from a balloon, but it appears to be quite an expensive and complex procedure (balloon setting up, demonstrator loading, ascent and launch) while loading and launching a missile from a fighter is a routine procedure.

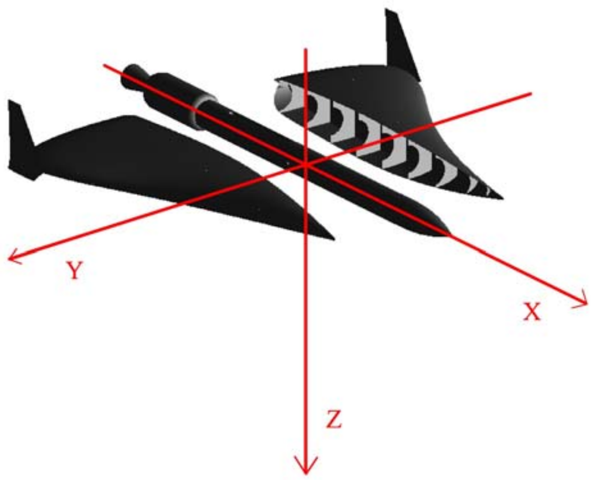

Fig.2: Technological demonstrator based on air-to-air missile

Regarding the data obtained thanks to the demonstrator:

- a modular conception has been adopted in order to investigate several aerodynamic configurations. All interchangeable modules, attached to the missile, do not hold strength function with the exception of bearing local pressure and thermal loads therefore they are light structures. They are mainly devoted to host systems and devices not contained in the missile, like parachute and airbags;
- the initial conditions that are in our case supersonic speed and an height of about 16 km seem to be more favourable than the ones of the X-34/L1011 system, while it has still to be studied the comparison with a launch from a balloon, i.e. from a greater height but without initial speed.

3. DEVELOPEMENT OF THE CONCEPT

Considering an air-to-air semi-active radar guidance missile like Alenia Aspide, the external dimensions of the technological demonstrator could be about 50% less than the ones of the Falke (see table 1). Figure 3 shows the Alenia (Lockheed) F104 Starfighter (interceptor aircraft of Italian Air Force) with the possibility of carrying two air-to-air missiles of the kind considered. The compatibility between the fighter and the demonstrator does not constitute a problem as figures 4 and 5 illustrate. In the first one the geometrical interface is shown, while in the second one the flight envelopes of F104 with and without air-to-air missiles are compared: no appreciable decrease in performances can be noted in the case of F104 carrying air-to-air missiles.

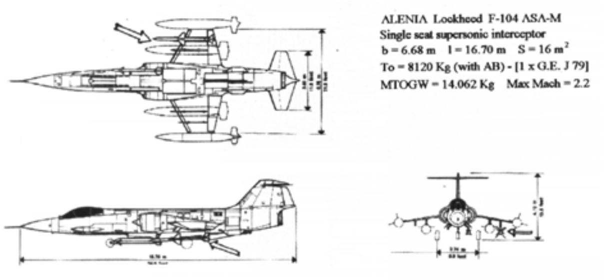

Fig.3: F104 with the air-to-air missile considered in the paper

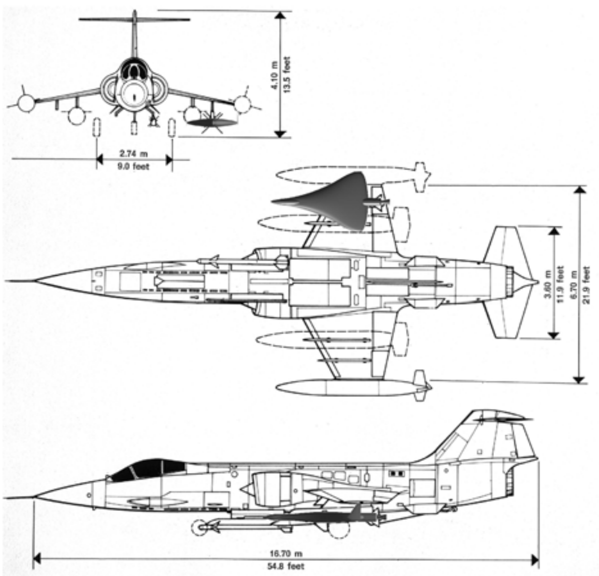

Fig.4: Geometrical compatibility between F104 and the demonstrator

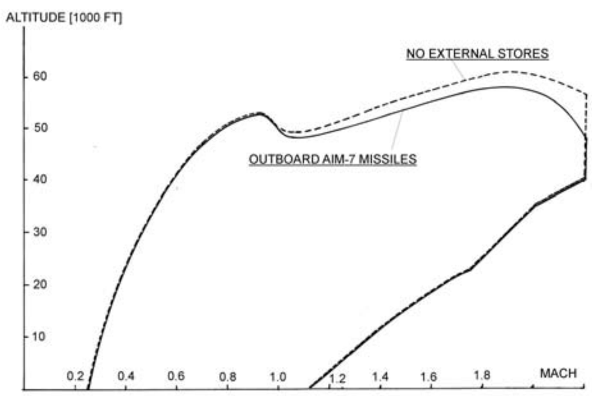

Fig.5: Flight envelope of F104

Taking into account the remarkable performances of the F104, as the rate of climb and the supersonic speed at high altitude, it can said that the F104 represents an interesting first stage for launching a technological demonstrator of the kind considered in our paper, even though the F104 has been in service for quite a long time now. Furthermore it can be remembered that, being the demonstrator based on one of the typical missiles used by Italian Air Force F104s, no serious problems regarding the mechanical and electrical interfaces between the aircraft and the demonstrator should arise. As far as the launch basis is concerned, a very good one could be located in the western part of Sicily island (figure 6), from where a trajectory could lie to the west without crossing any inhabited areas. This has to be guaranteed for safety reasons as items, like boosters after the early phase of autonomous flight, can be released.

Fig.6: Trapani: a possibile launch site

It can also be remembered that:

- Trapani airfield is a base of a F104 Squadron of Italian Air Force;
- near Trapani, Italian Space Agency (A.S.I.) has a base of balloons for atmospheric exploration. In case of launches from balloons, the fact that the two bases are close is an advantage from the logistics point of view.

4. DEVELOPEMENT OF DEMONSTRATORS CONFIGURATIONS

Let us now consider a typical semi-active radar guidance air-to-air missile, of the kind, size and characteristics useful to be the basis of our technological demonstrators, as discussed above.

Figure 7 shows the external shape and the main data of the hypothesized missile, while figure 8 describes the

missile internal layout and how it will be modified to accomplish the new and unusual role.
In particular we can notice:

- the large utilisation of missile's original subsystems, in particular the electronic package and auto-pilot, while engagement/attack avionics (mainly the radar system) could be maintained, or else replaced with other systems and/or payloads;

Length = 3700 mm
Body diameter = 200 mm
Wing span = 1000 mm
Boost time = 4.5 s
Flight time = 50 s
Speed = hypersonic
Range = 40 km
Solid propellant weight = 600 N
Thrust (medium/mean value) = 50000 N
Launch weight = 2200 N
Warhead weight = 300 N

Fig.7: Missile characteristics

- a useful telemetry package, that usually substitutes warhead in test flights, could obviously be maintained.

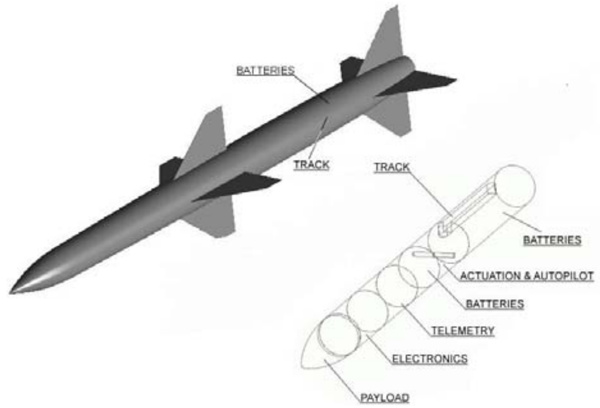

Fig.8: Missile internal layout (original and modified)

Solid rocket Engine	Function	Thrust	Boost time	Initial weight	Final weight	Diameter	Length
Rocketdyne 16NS-1000	Sustainer	4.46 kN	16.0 s	875 N	475 N	267 mm	890 mm
Similar to Rocketdyne MK38/39	Booster	52.0 kN	4.0 s	900 N*	300 N*	190 mm	1750 mm

* estimated values

Table 2: Solid rocket engines characteristics [2]

The original solid rocket engine has been removed, because of too short boost time even if with a high thrust (that would cause too high acceleration levels). So we have hypothesized the replacement of the original engine with a solid rocket Rocketdyne 16NS-1000 with characteristics (see table 2) more compliant with the function of "sustainer".
For affordability reasons the original engine (its characteristics are reported in table2) could be used as "booster" during the launch phase. It is fastened to the lower surface of the demonstrator. Because the diameter of the sustainer is bigger than the one of the missile body, it must be installed in the aft part of the body and on the same longitudinal axis to minimize the aerodynamic drag, as figure 9 illustrates. The rear part of the missile body has been cut off to shorten the demonstrator for geometrical compatibility with the launch aircraft and to make it lighter.
The missile, thanks to the removal of the standard engine, can host a remarkable electrical batteries package, which substitutes the original on board power unit of the missile. This is a high-speed turbine, fed by exhaust gas of a little dedicated booster, which drives an electrical generator and a hydraulic pump. The original power unit can generate a considerable amount of power, but for a very short time (less than two minutes). Thanks to the use of batteries, accounting also the further elements replacing the power unit, a longer supply time for on board electronics and other systems becomes possible. Furthermore it can be remembered that the demonstrator is not critical from the point of view of the power required to actuate the control surfaces.

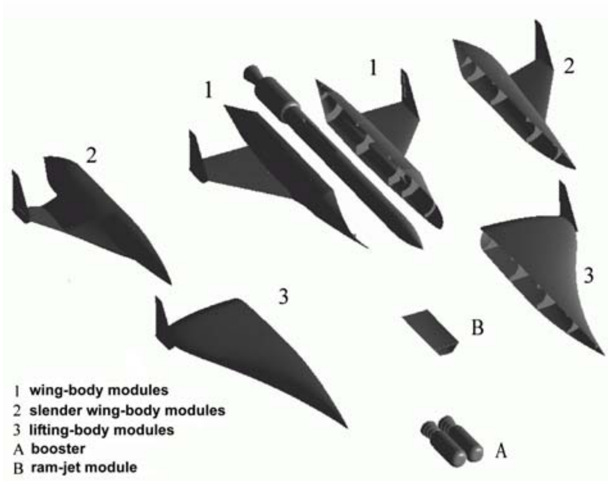

Fig.9: Modular conception

The trade-off between hydraulic and electrical actuators utilization for the technological demonstrator has still to be investigated. Anyway we believe that the choice of the electrical actuators could be more convenient, as it could avoid the adoption of the hydraulic system. In both cases the actuators will be installed in the same way in the missile as well as in the demonstrator. Anyway in the demonstrator the shafts, which in the original missile transmit motion to the four wings, will be the initial elements of mechanical rods connected to the control surfaces as the four central wings have now been removed.

The air-to-air missile, modified as discussed above and shown in figure 8, will be able to support interchangeable modules of the following kind:

a) additional propulsion modules, like boosters, of the kind mentioned in table 2 (one or two ignited one after the other), or else a bigger one, after checking the geometrical compatibility with the launch aircraft. The utilization and test of a little ram-jet engine would be really interesting. The employment of the ram-jet engine instead of the boosters implies also a different flight procedure as this time the sustainer engine has necessarily to be ignited before the ram-jet. As already mentioned, all propulsion modules will be attached to the demonstrators' lower surface;
b) three symmetrical modules connected to the missile body representing three different aerodynamic configurations:
   - wing-body;
   - slender wing-body;
   - lifting body.

   As already said, these modules will have mainly shape functions and will be devoted to host devices like re-entry parachutes and air-bags and liquid fuel (and related feed system) in case of ram-jet module installation.

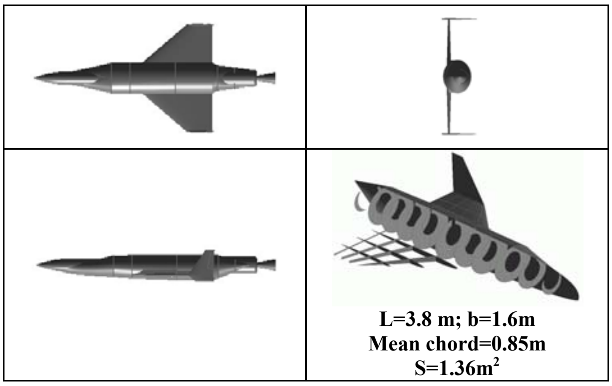

Fig.10: Wing-body configuration

Figure 9 sums up this modular conception, while the following figures 10, 11 and 12 illustrate the three different aerodynamic configurations that can be obtained. For every configuration the main geometrical data are reported and a very preliminary weight estimation (in first approximation applicable to all configurations) is given in table 3.

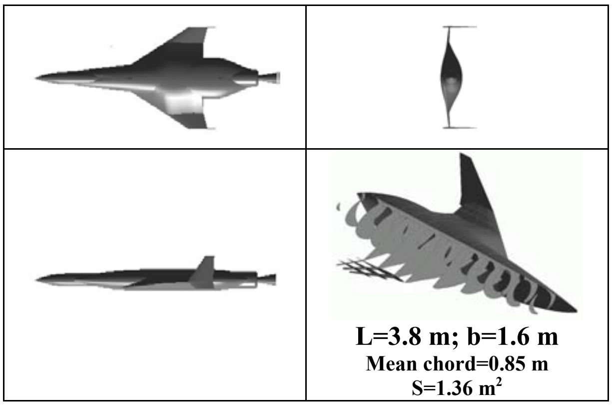

Fig.11: Slender wing-body configuration

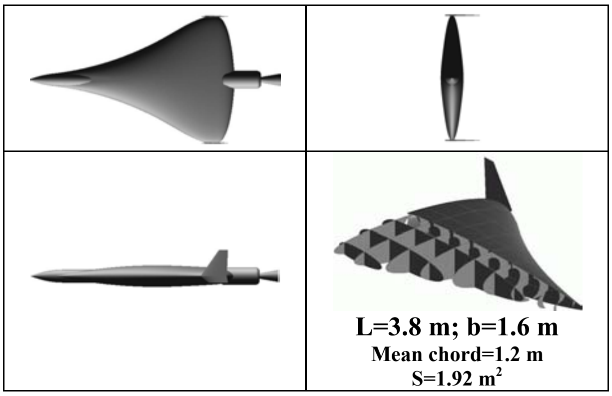

Fig.12: Lifting-body configuration

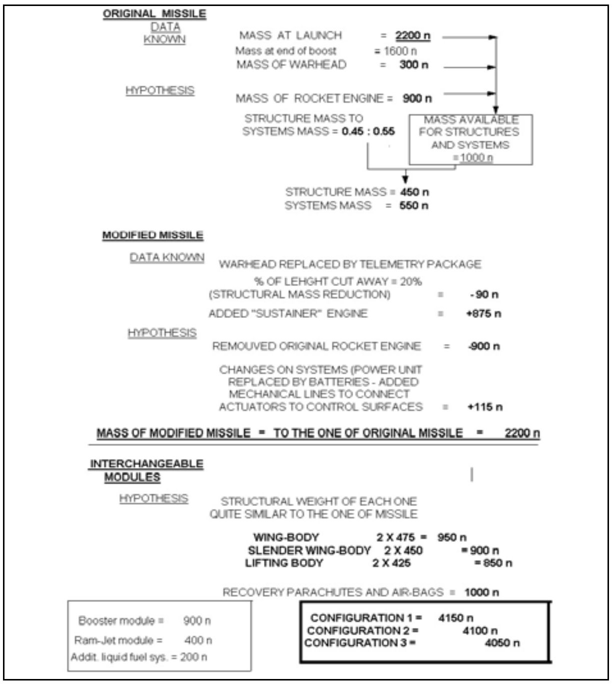

Table 3: Preliminary weight estimation

5. PERFORMANCES PRELIMINARY EVALUATION

A simplified algorithm of simulation in the time domain has been used in order to obtain a preliminary evaluation of the performances of the demonstrators' family.

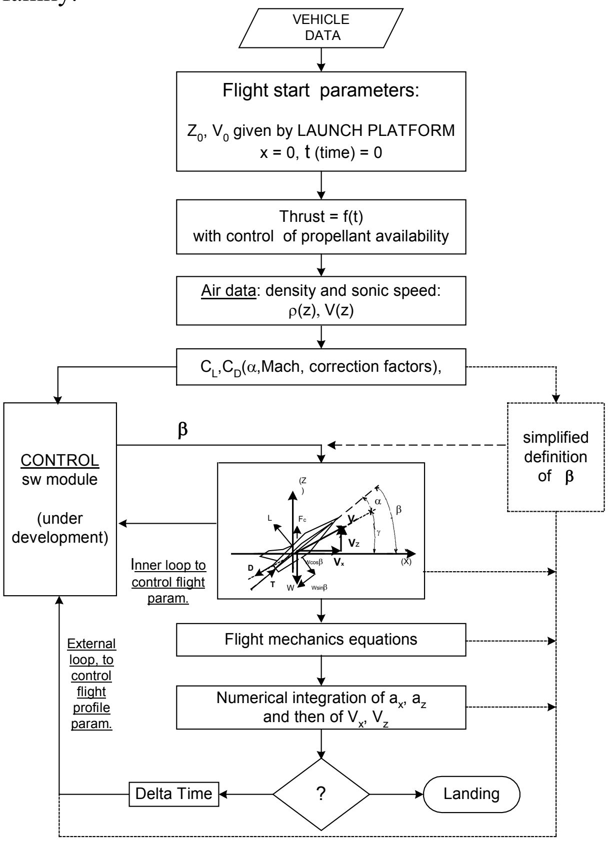

Fig.13: Flowchart of the simulation program

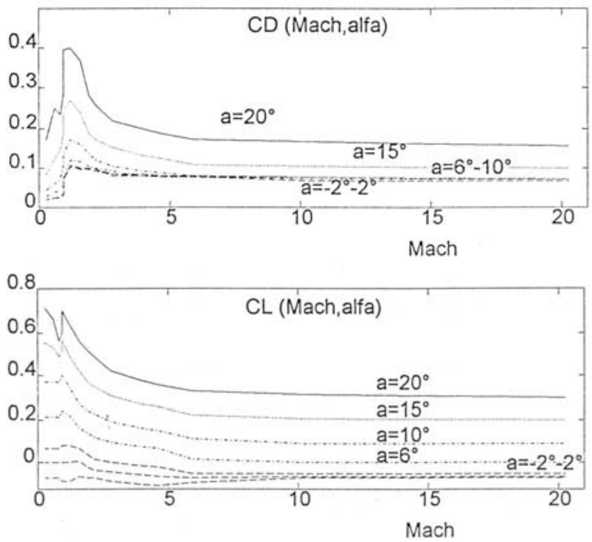

Fig.14: Aerodynamic data base[3]

Figure 13 illustrates the flow chart of this algorithm while figure 14 shows the aerodynamic data base, adopted in our simulation program, of lift and drag coefficients as functions of the Mach number and the angle of attack.

These aerodynamic data refer to an SSTO-VTOHL vehicle. Empirical coefficients have been defined to correct the values of the drag coefficient in order to take into account:

- the aerodynamic behaviour of shapes, like the slender wing-body and the lifting body configurations, which are more efficient than the wing-body one;
- the aerodynamic behaviour of different shapes due to the adoption of various additional propulsion modules, like one or two boosters or the ram-jet engine;
- the changes of shape during the flight when an external booster is released.

The variable of control that we have chosen, that is the pitch angle β, assumes values that have been defined on the basis of previous experience in order to obtain a preliminary rough mission performance evaluation. We are currently working together with a research group of the Control Laws and SW Department at our Polytechnic to carry on the ongoing research aiming at obtaining an optimised flight profile. The definition of a control SW module integrated into a close loop with our simulation program will supply the control variables that we need.

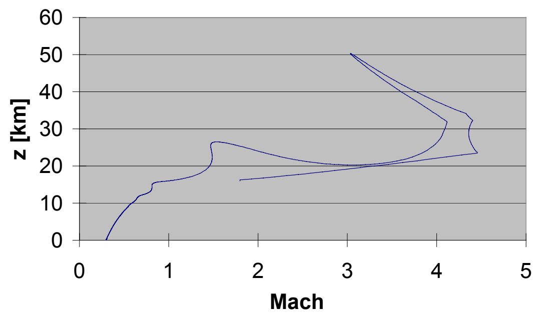

Fig.15: z(Mach) graph for the slender wing-body configuration

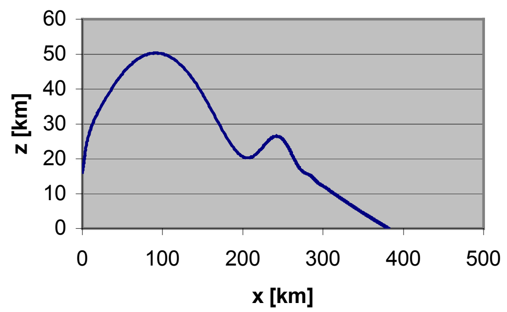

Fig.16: z(x) graph for the slender wing-body configuration

As an example of the results obtained, figures 15 and 16 respectively illustrate the $z = z(M)$ and the $z = z(x)$ graphs relevant to the slender wing-body configuration with the propulsion system constituted by

a sustainer solid rocket and two boosters (figure 9 and tables 2 and 3) ignited one after the other immediately after the launch at supersonic speed from F104 aircraft.
Figures 15 and 16 point out:

- the launch coordinates;
- the ascent phases employing the different kinds of engines;
- the phase of ascent due to inertia;
- the coordinates corresponding to the maximum Mach and altitude reached;
- the descent phase (that is certainly subsonic below 11000 m);
- the landing phase (without considering the parachute action).

A great number of simulations have been performed, considering:

- several kinds of launch:
  - from a F104 (16 km height, supersonic speed);
  - from a subsonic aircraft that could be a jet liner/executive or, for affordability reasons, a subsonic combat aircraft, like the Italian Air Force AMX (9 km height, subsonic speed);
  - from a balloon (40 km, zero initial speed);
- three aerodynamic configurations;
- different kinds of propulsion systems:
  - sustainer with one or two boosters;
  - sustainer;
  - sustainer and ram-jet;
  - no propulsion: gliding descent.

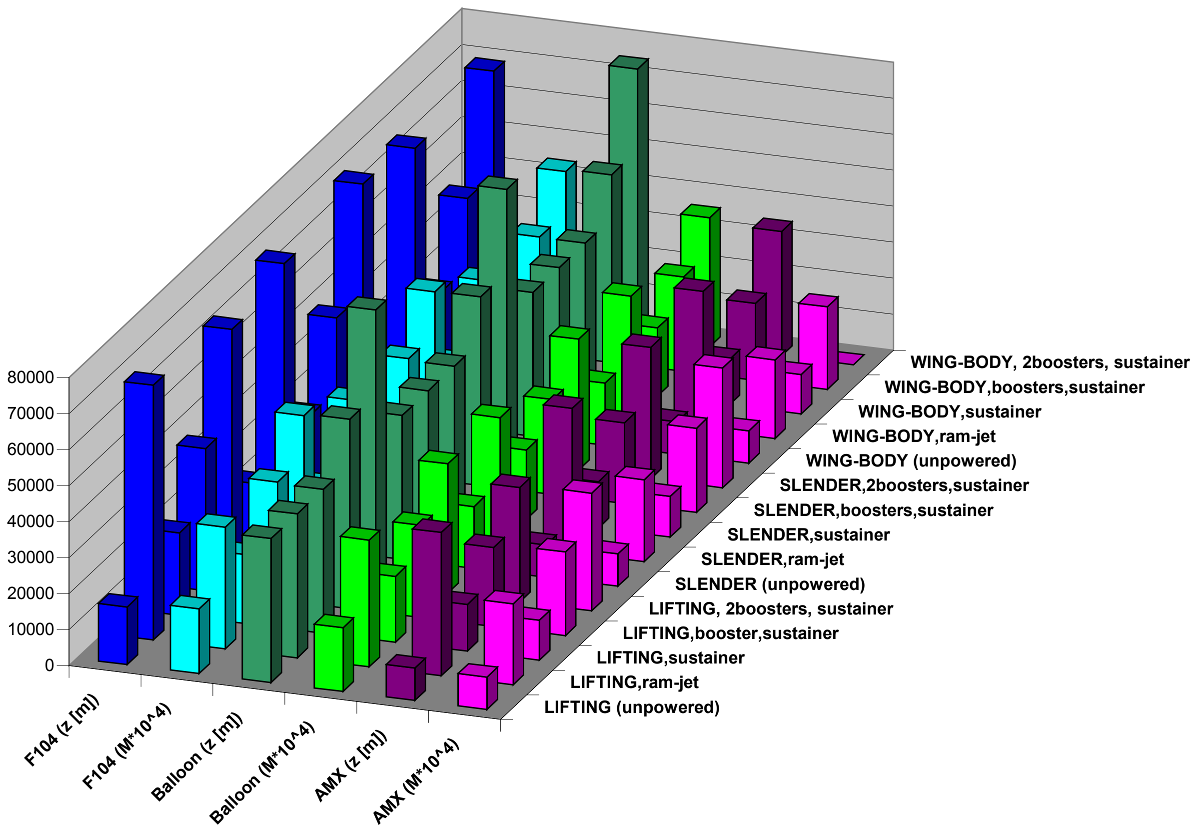

Fig.17: Comparison of the simulation's outcomes

Figure 17 sums up and compares the simulations outcomes. They are encouraging even if the flight profile optimisation algorithm has not been applied yet. It can be easily noted that the values of Mach and height reached in case of launch from AMX are worse than the ones obtained in the other two cases. Taking into account the affordability and the slightly higher values of Mach number, roughly it can be said that the utilization of F104 as launch aircraft appears to be more cost-effective.

We hope we can carry on the project, probing into the following fields:

- optimisation of the flight trajectory and mission profile, which is now underway in cooperation with Control Laws and SW Research Group;
- more detailed design definition.

Figure 18 is a preliminary study for the layout and Digital Mock-up definition (methodology in which the research group is particularly involved [4]). Figure 18 seems to confirm the volume availability for all devices that could be hosted like ram-jet liquid fuel system, parachute and air-bags and to verify the preliminary weight estimation for parachute and air-bags (see table 3). It is also possible to perform a first rough structural analysis using a classical methodology [5] [6] on the basis of the hypothesized structural layout.

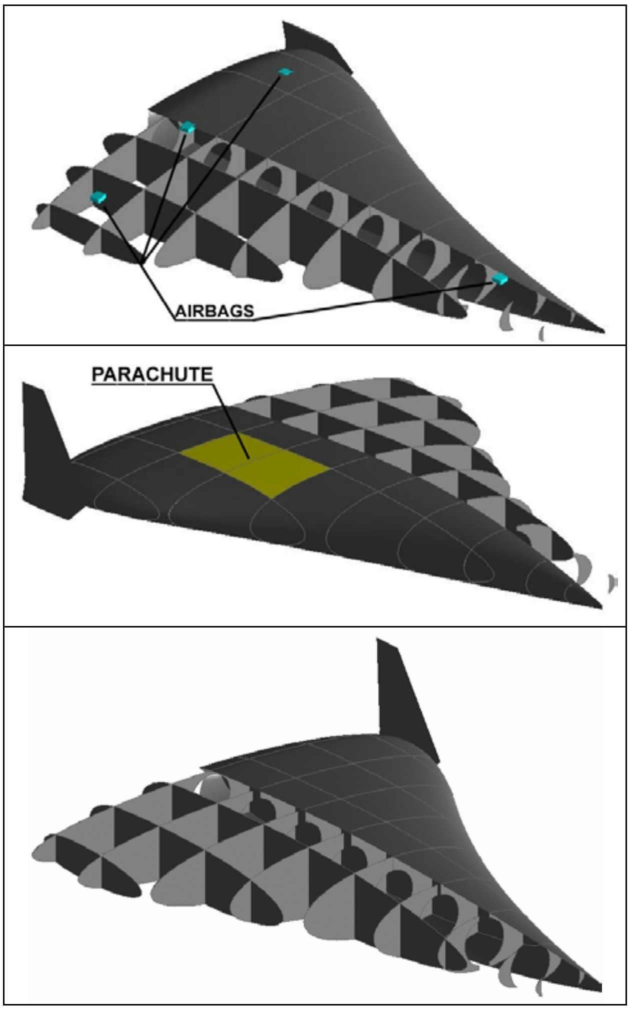

Fig.18: Structural layout for the lifting body configuration

Our next targets will be:

- a general assessment of all thermal aspects involved in cooperation with a research group of the Energetic Department;
- studies regarding manufacturing of the product, its operative life and related costs to achieve a more realistic and complete definition of the project.

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