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Status and Perspectives of Hypersonic Systems and Technologies with Emphasis on the Role of Sub-Orbital Flight *

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Abstract

The relevance and the main features of Hypersonic Flight are shortly presented and discussed. A synthetic overview of the few realisations and of many studies, projects and technological demonstrators offers opportunity of point out many interesting aspects. Then the more actual realisations and studies are considered, with particular attention to the new sector of small suborbital planes for Space Tourism. That gives opportunity of proposing a Road Map for an affordable and logic development of Hypersonic Flight, passing through the development of a suborbital Space Tourism plane on the basis of an existing subsonic business jet. Then the suborbital plane will constitute the basis of developing an Hypersonic Cruise Business Jet and, as a next step, a TSTO.

1. Introduction

The hypersonic flight is a subject on which the efforts of basic and applied aerospace research have been focused over the years. These efforts consisted in the development of several projects and corresponding technological fields, such as aerodynamics, propulsion, structures capable of withstanding high thermal stress, the system design, etc. By considering such efforts, if great progresses have been achieved on the side of the technological insights in most of the areas covered, very poor results were obtained in terms of realization of operational products; the only practical achievements were experimental vehicles or technological demonstrators, capable of performing only partially the mission of a real hypersonic aircraft, and consequently with low operational capability. The aim of this work is to summarise the great mass of accumulated experiences and, considering the current achievements and projects now under study, to suggest strategies that can promote advancement in the field, in particular leading to the development of hypersonic aircraft more and more complex, tending to achieve a complete and mature ability to fly hypersonically.

2. Hypersonic Flight Concept

It is considered appropriate to establish a definition of hypersonic aircraft, useful to define the topic of discussion; we define hypersonic aircraft a system capable of taking off and landing horizontally (HOTOL - Horizontal Take Off and Landing), and capable of flying at a Mach higher than 4.5. Please note that exceptions regarding the takeoff may befound, as:
a) aircraft VTOHOL - Vertical Take Off and Horizontal Landing - can be conceived, that is a solution imposed by technological constraints and in any case not to be considered definitive
b) Always for "not definitive"aircraft (and therefore for many of the "technology demonstrators" realized) the landing may be horizontal but not on runway, with a landing gear like airplane, but with parachute and / or paraglide, on ground or on water. As to the ability of achieving hypersonic speed (for characterization of the aerodynamic behavior at high Mach numbers greater than 4.5, please refer to the many excellent texts, particularly [1]) we can make some considerations:
a) When hypersonic speed (Mach 4.5 or even more) has been reached, if the plane can sustain such speed for periods of the order of a few hours, it will obviously get extremely interesting autonomies of flight. The hypersonic cruise (for containment of dynamic pressure values and then for containment of structures heat-

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ing) must be carried out at altitudes of about 30 km or more, i.e. at altitudes higher than those of the subsonic jet airplanes (9-12 km) and of those, higher, of the SST (Supersonic Transport) like the Concorde (17-18 km).
b) By considering, with reference to the previous point, the flight altitude at which hypersonic speed can be reached, at conceptual level it can be hypothesized that the energy, in the previous case used to support the hypersonic cruise, could be instead utilized for further increasing altitude and speed. In case when both the speed and altitude increase, it can be assumed that the reduction of aerodynamic lift (because of the decrease of the atmospheric density and despite the increase in speed) is compensated by the effect of centrifugal force due to the curved trajectory (because of the terrestrial curvature), with the possibility of reaching the orbital speed [2] at a given height (generally at least 100 km for containing the atmospheric drag). In this case, the hypersonic vehicle, capable of achieving a low orbit around the Earth and, of course, in case it transports payloads, can be defined orbital transport. It is clear that, through a de-orbiting maneuver, the aircraft will return to earth with a trajectory, without propulsion, except any action of slowing down or braking. This return trajectory will be critical in order to the capacity to dispose all kinetic and potential energy possessed. If the carried payload will consist of artificial satellites to be released in orbit, we can define the vehicle a Reusable Launcher-RL.
c) An intermediate situation between the two above considered is to climb at altitude of the order of orbital ones, even without reaching the orbital speed, proceeding then to a trajectory of descent (non-propelled), with ability to return to land far from the departure point; with this type of "sub-orbital" flight, range and flight duration comparable with those seen in the previous point a) can be obtained. The three types of hypersonic missions just described are schematically shown in Figure 1.The 3 different types have of course different characteristics and utilization strategies, but they show affinities and a common logical ratio that is summarized in Figure 2. In this figure we show how, starting from the need of increasing speed and range of flight for air transports (in order to make accessible in a few hours any point on the Earth) we have to increase the flight altitude and to adopt different engines from turbojets (which, even with after-burner, cannot fly over Mach 3.5) obtaining a type of machine that we can define "AirSpacePlane".

Figure 2 also shows that a similar result can be reached, by imagining that we want to make "reusable" a Launcher by providing it with a lifting surface that allows it to return to ground safely, after its mission has been performed. From this first step, the next is to use such lifting surface also for the phase of ascent, with a trajectory that, compared to that of

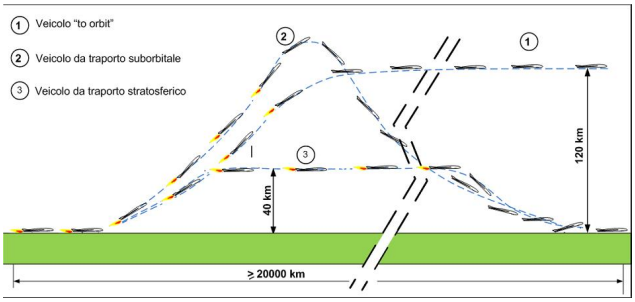


Figure 1. Kinds of Hypersonic Planes. [3]

the Vertical Take Off-VTO Systems such as rockets, provides a much more long stay in the dense layers of the Earth atmosphere (Figure 3); this leads to the opportunity of providing "air breathing" engines even if with constraint of switching on the Ramjet over Mach 3.5.
In this way we confirm that three different kinds of Hypersonic Planes can be envisaged, i.e. the ones capable of sustaining hypersonic cruise without further increase of altitude and speed, or the others capable of increasing altitude and speed, both till to reach the orbit or to perform suborbital flight aimed to cover extended ranges on the Earth surface.It should be noted that the boundary of Mach 6.5 for the Ramjet imposes, for higher speed, the switch to either the Scramjet (Supersonic Combustion Ram-Jet) or the Rocket. The Scramjet technology is not fully acquiredyet and there is a doubt concerning the speed limit while, certainly, there is one about the altitude as, in any case, an air breathing engine cannot be able to operate in vacuum, while the rocket, as known, will not have any constraint of operation.Figure 4 reminds how the Specific Impulse for various kinds of engines evolves with Mach. It is clear the opportunity of using the types with better specific impulse just till the speed at which they must be substituted by another engine with lower specific impulse. In any case it is clear the advantage, for each kind of engines, to use, as fuel, LH2 rather than hydrocarbons.
With regard to the aforesaid considerations about engines and reminding that Ramjet and Scramjet have also a lower limit of speed for their operation, in Figure 5 we present the more logical combinations of engines that can be envisaged for Hypersonic Planes with different values of maximum speed and maximum altitudes that they can reach.
To complete the overview of theHypersonic Planes possible configurations, we have to consider the possible adoption of a multi-stage solution, aiming to the same advantage in order that it is absolutely mandatory for Reusable Launchers; in factit is well known

that advantage lies in ridding the vehicle itself by the no longer necessary parts (i.e. "inert masses") due to the progressive exhaustion of the propellants. The downside is the criticality in the operation of separation and the duplication of Crew or GNC Systems (in the case of "Unmanned" solutions) for the return to earth of the early stage (Figure 6). To this regard it is important a basic choice to be made when the project of a Two Stages Hypersonic Aircraft is set up, that is how to use the engines of the two stages in Take Off and initial climb.

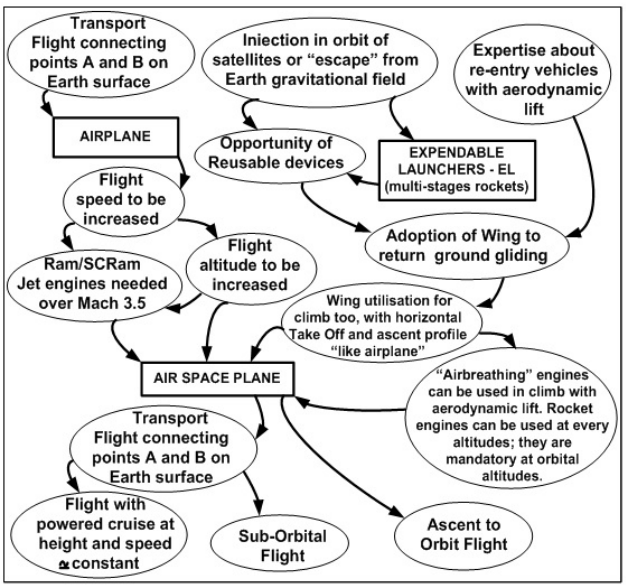


Figure 2. Logic path to define Hypersonic Vehicles typologies. [3]

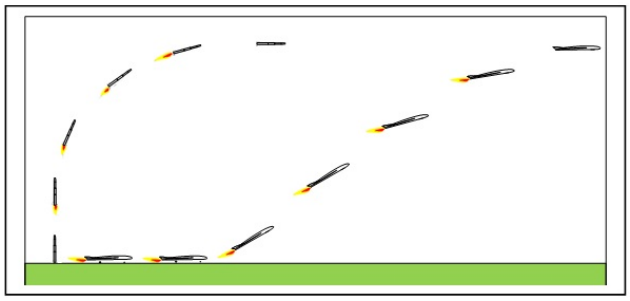


Figure 3. VTO and HTO Systems ascent trajectoriescomparison. [3]

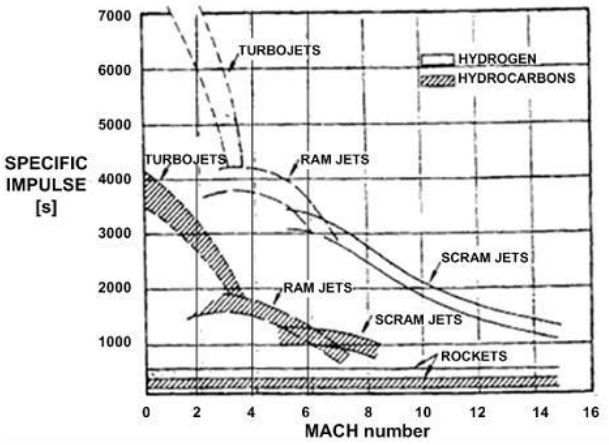


Figure 4. Specific Impulse of several kinds of engines as Mach function. [3]

TURBOJET with A.B.	RAM JET			Limited to Mach 6. Typical solution for stratospheric cruise airplanes. Turbojet and Ramjet separated or integrated.
TURBO FAN.	ROCKET	RAM JET		As in previous case but with engines more eco-friendly for low altitude phases of flight. Rocket needed to reach ignition speed of Ramjet.
TURBOJET with A.B.	RAM JET	SCRAM JET		Technology still to be examined in depth. Altitude and speed achievable still to be defined.
TURBOJET with A.B.	RAM JET	SCRAM JET	ROCKET	Orbit achievable. Optimal Engines sequence. System complexity.
TURBOJET with A.B.	RAM JET	ROCKET		As previous case, but avoiding Technology not totally acquired yet.
ROCKET	RAM JET	ROCKET		Orbit achievable. Simple System but high consumption.
ROCKET				Simple System, but very high consumption to orbit; more useful for SubOrbital flights.

Figure 5. Possible Propulsion Configurations for Hypersonic vehicles.

Figure 7 summarizes three options:
a) At the takeoff and climb the engines of the first stageare active, while those in the 2nd will start only after the separation. It is the classical solution, with the simplification of no transfer of propellants between the stages and the advantage that the two stages can be provided with the most suitable engines taking into account different speed regimes (e.g. Turbo Ramjet on 1st stage and Rocket on the 2nd). The disadvantage is that in the critical phase of the take-off the engines on 2nd stage do not contribute.
b) On the contrary, it is possible to use also the engines of the 2nd stage at take-off, with possibility of transferring propellant from the 1st to the 2nd stage, in order that such 2nd stage can still have the tanks full at separation. Obviously the engines of the 2nd stage, in many cases rockets, at low speed will contribute to the thrust certainly, usefully, but at the cost of high

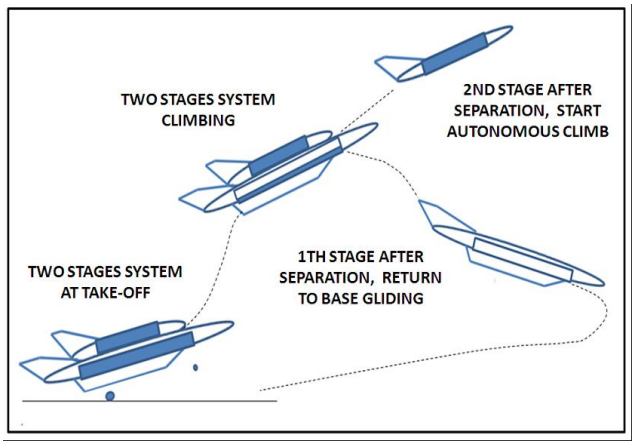


Figure 6. Two Stages Air-Spaceplanes. [3]

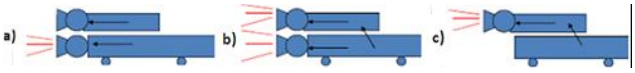
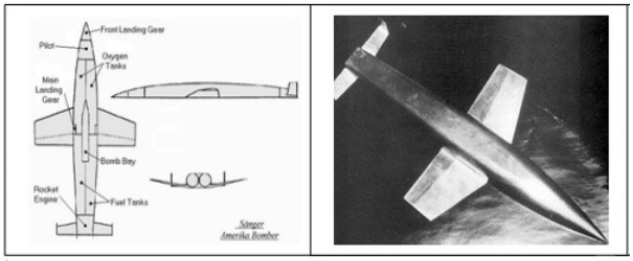


Figure 7. Two Stage Propulsion Configurations. [3]

consumption.
c) Finally, we can radicalize the previous concept by providing engines on the 2nd stage only, while the 1st become a big container of propellant to be transferred to the 2nd stage. The 1st stage howeverwill have a wing for the ascent with aerodynamic lift and that, after the separation, will allow the return, of the stage, in gliding flight, to the Base. The advantage is the simplification of the propulsion system, compared to a minor energetic optimization of propulsion respect to the phases of flight. These considerations confirm how the configuration chosen for the "Staging", i.e. single or two-stage, and if two-stage, what kind, is closely related with the choice of propulsion system configuration, that is how many kinds of engines and with which sequence. Finally, always with regard to the two-stage configuration is to be noted that a dramatic choice is that of the speed (and altitude) of separation: examining the many studies and projects available in the literature two types of choices are present:
- Separation at an altitude between 25000 and 35000 m at speed between Mach 5 and 6.5.
- Separation at an altitude of between 9000 and 11000 m at high subsonic speed; the advantage may be to use as a 1st stage an existing, usual, subsonic airplane.

3. Overview of Hypersonic Airplanes

To consolidate what is stated in the previous point it seems useful to proceed to a brief review of the main Hypersonic Planes gradually studied. The first design to be considered is certainly the "antipodal Bomber" project carried out in Germany by Eugen Sanger from the mid-30s and updated until the end of WW II. As shown in Figure 8 it was a single-stage rocket powered with a suborbital flight profile. It was expected to reach speeds and altitudes near the orbital ones, from which to begin a long descent, with successive "bounces" back to the dense layers of the atmosphere, in order to obtain considerable autonomy (Figure 9). Having in mind that the purpose was to bomb New York, starting from Germany, then returning to Japan (or, in advanced version, to Germany) and that the engines were the same of the two-stage missile A9/A10 (also aimed to hit New York [3]), it is evident a common origin for two categories of EL and RL (or, more generally, Hypersonic Aircraft).



SINGLE STAGE SUB-ORBITAL
Wing Span: 15 m
Length: 28 m
Empty Weight: 10-12 tons
TOGW: 100 – 130 tons
Thrust: 100 tons
Time of Propulsion: 270 – 480 s
Maximum Speed: 22000 km/h
Maximum Altitude: 145 – 280 km
Range: 20000 – 30000 km

Figure 8. Sanger Sub-Orbital BomberConfiguration, Aerodynamic model, Technical Data.

Beyond some conceptual errors that would not allowa practical realization, for many other aspects the technical choices of the project of "antipodal bomber" Sanger appear to be correct and still actual, making this project the true progenitor of Hypersonic Aircraft. For the same reason it is surprising that the idea did not develop, favoring EL.A remarkable exception, however, is the "Soviet antipodal Bomber", a Soviet study extremely inspired by the "Sanger Bomber", in which, however, the introduction of two Ramjet engines (Figure 10) shows the choice of a stratospheric cruise at hypersonic speeds, instead of the suborbital

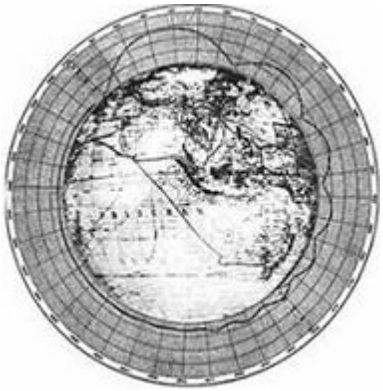


Figure 9. Sanger Bomber Mission Profile (from Germany to Germany).

trajectory for the achievement of large distances (to the limit "antipodal"). However, even this project was not further developed.

Figure 10. Soviet Antipodal Bomber; configuration and Technical Data.

It was only in the last 15 years of the twentieth century that a real flowering of Hypersonic Aircraft projects appeared, that was dictated by the need to expand autonomy and reduce the time of flight of the long range aircraft and to obviate the cost of the EL [4]. Among these projects particularly significant are the U.S.NASP X30, the English HOTOL and the German Sanger II, respectively shown in Figures 11, 12 and 13. NASP X30 was a SSTO also meant to be used as hypersonic transport and assumed the use of Scramjet. Also the HOTOL was an SSTO characterized by using a specific propulsion system, the Rolls Royce RB 545, capable of functioning either as air breather and, above Mach 6.5, as rocket.

The Sanger II was a TSTO with the first stage, powered by integrated Turbojets and Ramjets, usable also as hypersonic transport and with the second stage propelled by rocket.

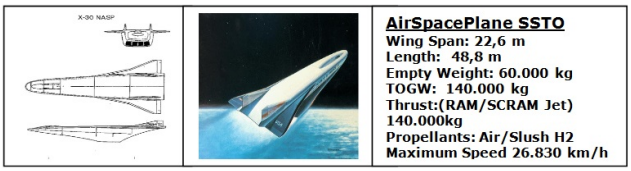


Figure 11. NASP X 30 Three views drawing, Pictorial representation, Technical Data.

Figure 12. HOTOL Three views drawing, Pictorial representation, Technical Data.

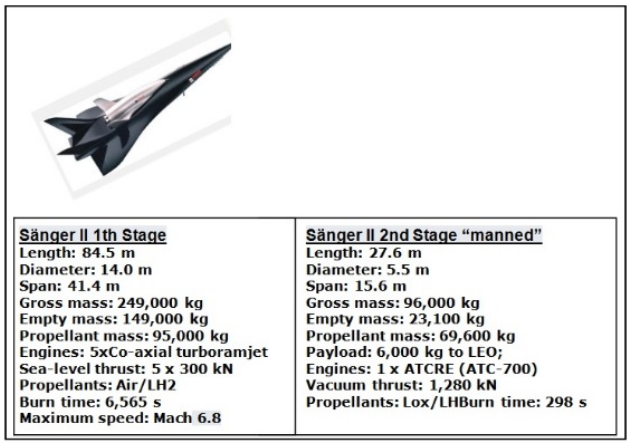


Figure 13. Sanger II Pictorial representation, Technical Data.

4. Present Situation

Unfortunately, none of the projects of Hypersonic Aircraft developed in the last years of the twentieth century could be realized, for both technical difficulties and, even more, for financial reasons. Fortunately, after a lost occasion, another oneappeared;it was certainly more modest but also characterized by a remarkable vivacity of ideas and the involvement of new actors, in particular many new small industries, able to deal with the problem of space transportation with a simple and not cumbersome approach like the one

of large companies. The need to reduce the costs of access-to-space and the failure in doing so with the classical governmental space agencies approach, suggested a new trial: close up the gap between aeronauticsand space [10]. The new fact was the idea of the "Space Tourism", i.e. the idea of offering, to a growing number of people, the possibility to "live the experience of an Astronaut". It was immediately understood that in order to have a minimum of diffusion of space tourism and to make the activity a source of profit, it was necessary to think about "minimal" space missions, conducted with vehicles that presented incomparably lower costs e.g. compared to those of the Shuttle. The "minimal" space mission were identified in a suborbital flight, without the need to reach the orbit, and with maximum speeds of the order of a few Mach numbers.From a psychological point of view, however, making a ballistic trajectory such as that shown in Fig.14, can be sufficient to experience microgravity conditions (although limited to a few minutes)at the top of the trajectory; moreoverat altitudes over 50 km, looking outside the airplane, it is possible to see the curvature of the earth and, being above the dense layers of atmosphere, the typical vision of the "black sky", these are all typical aspects of space travel.

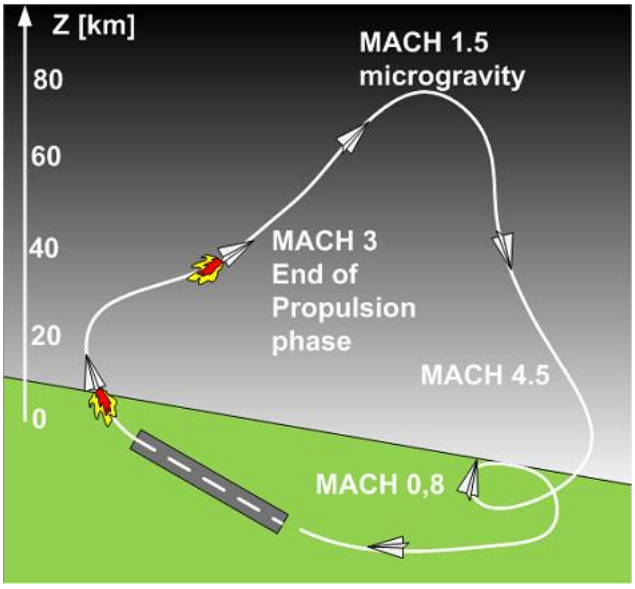


Figure 14. Space Tourism sub-orbital flight [3]

Consequently, in view of profit, it opened the way to develop small aircraft to accomplish missions of the type described, with at least some passengers in addition to the pilot. In Figure 15 some of the projects developed in the 2000s are briefly mentioned. Many of them were conceived to participate in the so-called

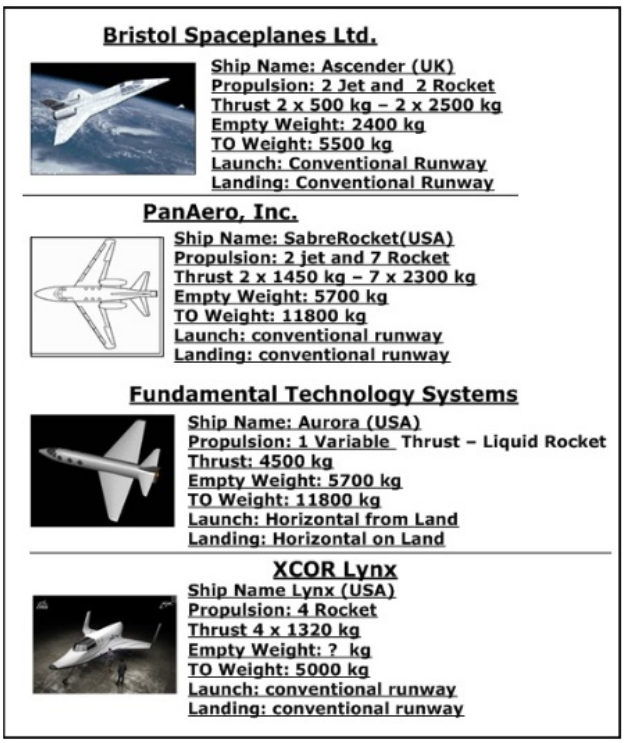
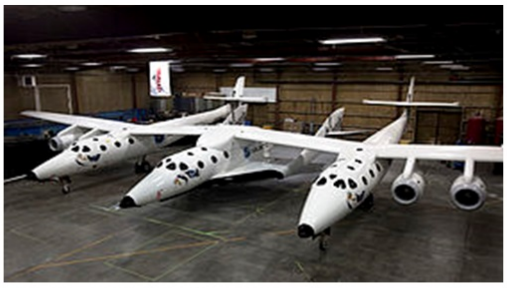


Figure 15. Sub-orbital Vehicles for Space Tourism.

"X-Prize", a prize of U.S. $ 10,000,000 offered by a Foundation established for the purpose, to Who, first, could "create an aircraft capable of carrying at least 3 passengers at a minimum of 100 km altitude, that could be completely re-usable and able to accomplish at least two missions in two weeks". The winner was the "Space Ship One", a 2nd stage rocket powered spacecraft, launched at subsonic speed from the jet powered "White Knight One" aircraft, both conceived by the famous designer Burt Rutan. The larger version "Space Ship Two / White Knight Two" (Figure 16) appears next to begin soon regular tourism flights.

Other projects of airplanes to space tourism, as XCOR "Lynx" (rather small, single-stage, powered by only rockets - see Figure 15), seem near to materialize. While in the field of Space Tourism mainly SME was involved, large Aerospace Companies and Research Centers focused mainly to the development of technology demonstrators, systems able to comply with mission profiles only partially corresponding to that of a trans-atmospheric aircraft, e.g. in many cases vehicles capable of returning from orbit where, however, have been brought from EL. Also vehicles with a certain degree of operability such as the Boeing X37 and the future Dream Chaser (with 7 passengers) are to be mentioned, while, as regards demonstrators totally or largely developed in Italy, CIRA USV and IXV are



SPACE SHIP TWO	WHITE KNIGHT TWO
Crew: 2	Crew: 2
Capacity: 6 passengers	Payload: 17,000kg at 15,000m
Length: 18.29 m	Length: 24 m
Wing span: 8.23 m	Wing span: 43 m
Height: 4.57 m	Powerplant: 4 ×P.& W. Canada PW308 turbofan
Powerplant: : 1 x Hybrid Rocket	Thrust: 30.69 kN x 4
Max. altitude: 107 km	Max. altitude: 21,000 m
Max. speed: Mach 4	

Figure 16. Space Ship Two & White Knight Two.

shown in Figure 17-a, on the bases of which the ESA PRIDE-ISV program has been generated and formally approved during the ESA Ministerial Council held in Naples in November 2012 (Figure 17-b).

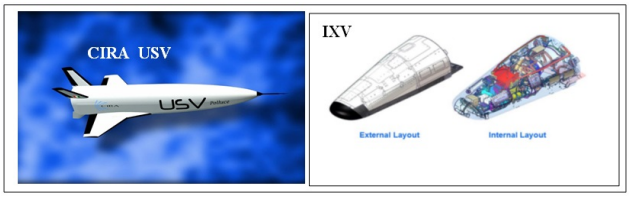


Figure 17. Italy-led Reentry Vehicles Demonstrators.

As to studies of complete aircraft, a few cases can be mentioned:
a) The Orbital Transport (so a RL) called SKYLON (Figure 18) due to Reaction Engines Ltd, established at the time of closure of the program HOTOL already mentioned, to keep alive the most distinctive technologies. In particular, Reaction Engines has continued to work on specific engines RB545, perfecting them in the so-called SABRE engine (characteristics quite similar to the ones of RB545 but with a considerable reduction in consumption). The SSTO SKYLON is a derivative of HOTOL but with twoSABRE engines and with different architecture aimed to eliminating large displacements of the CoG with the progressive consumption of propellants, defect that had negatively disadvantaged the HOTOL. Reaction Engines is optimistic and is predicting the realization of the prototype

Figure 18. ESA PRIDE ISV Reusable Reentry Demonstrator.

SKYLON within few years.

SKYLON
Crew: None, remote controlled from ground.
Capacity: Potential for up to 30 passengers
Payload: 15.000 kg (33,000 lb)
Length: 70 m
Wingspan: 22 m
Fuselage diameter: 6.75 m
Empty weight: 53.000 kg
Loaded weight: 345.000 kg
Powerplant: 2 × SABRE 1,350 kN eachThrust/weight: ∼1.2 – 3 at burnout (∼0.768 atmospheric)
Specific impulse: 3500 s atmospheric, 450 s exoatmospheric
Service ceiling: 26.000 m air breathing, >200 km exoatmospheric
Maximum speed: Orbital (airbreathing Mach 5.5)

Figure 19. SKYLON Pictorial representation, Technical Data.

LAPCAT A2	
Type: hypersonic passengers transport	
Pax n°	300
Length	139 m
Wing span	41 m
Wing area	900 m²
Take Off Gross Weight	400.000 kg
Fuel Weight	198.000 kg
Engines	4 Scimitar Cruise
Speed	Mach 5
Range	18700 km
Unit cost (estimated)	639 M€

Figure 20. A2 LAPCAT, Pictorial representation, Technical Data.

b) The concept LAPCAT A2 is a transport passenger (over 300) at velocities of Mach 5 with "antipodal" autonomy. Also this project is due to Reaction Engines Ltd, and its architecture is partially similar

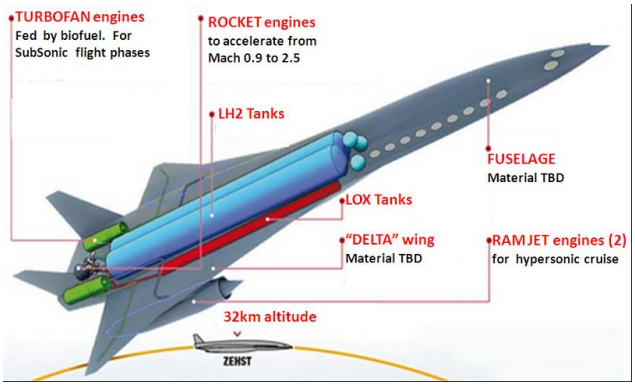


Figure 21. ZEHST configuration and Vehicle characteristics.

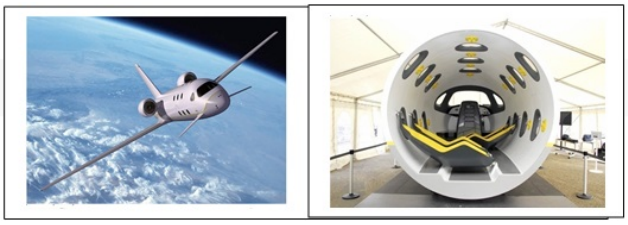


Figure 22. Space Tourism EADS; pictorial view and passengers cabin layout mock-up.

to the one of the SKYLON, and is powered by four engines called SCIMITAR, derived from SABRE with limited functionality to "airbreathing" operations.
c) The project ZEHST-Zero Emissions HyperSonic-Transport (Figure 20) due to EADS. Even in this case we have a Passenger transportation (though limited to about 60) but the aircraft uses, in succession, three different types of engines, turbo fans that are powered by biofuel for subsonic flight phases at altitudes lowerthan 10 km, Rockets fed by LOX and LH2 to accelerate to the speed useful for the ignition of the 3rd type, i.e. Ramjets (fed by LH2)for the hypersonic cruise.
d) The EADS Group has proposed a sub-orbital Space Tourism project (Figure 21), whose feasibility is obviously much more probable.

5. Possible Road Map to Contribute to Develop Hypersonic Flight

On the basis of previous considerations we can consider that the hypersonic flight is today a field technologically mature, but whose development is hampered by economic (difficulty in obtaining the necessary substantial financial resources) and organizational factors (difficulty for the great trusts, because of differences in goals and ways of working); in this latter regard it is noted as today most advanced projects are those of small companies, such as various aircraft for Space Tourism, as well as the projects developed e.g. by Reaction Engine Ltd. It is very well clear that the Return Of Investment (ROI) for such kind of enterprise is quite long (around 10 years), and this represents another hampering factor. However, it must be recognized that the very same situation appeared when the car was introduced during the first years of XIXth century, as well as when the airplane was developed at the beginning of the XXth century. And we could quote the railways, the ships, and many other manmade instruments. This means that, following the previous mankind experiences in other fields of engineering, space tourism first and hypersonic aircrafts will soon demonstrate to be new transportation means, whose development and diffusion will soon involve more and more persons, becoming before we can expect enough cheap to be available to everybody.
Starting from the strong conviction that the Hypersonic Flight must be developed, we intend to propose here a "Roadmap" for possible activities to contribute to this development, attentive to financial aspects and believing in the quick appearance of new small industrial entries aligned with theview of Space Renaissance Italia [5]. The Roadmap is summarized in Figure 22, which shows that, in the aforesaid points of view, the first product to be realized is a suborbital Space Tourism plane. The idea is that this product can be profitable; in this way it would make, at least in part, the subsequent self-financed "STEP 2" and STEP 3 "targeted to the realization of two other "finished" products, i.e. an airplane with hypersonic cruise with few passengers (so a "Hypersonic Business Jet") and a transportation system of the type of Orbital TSTO.

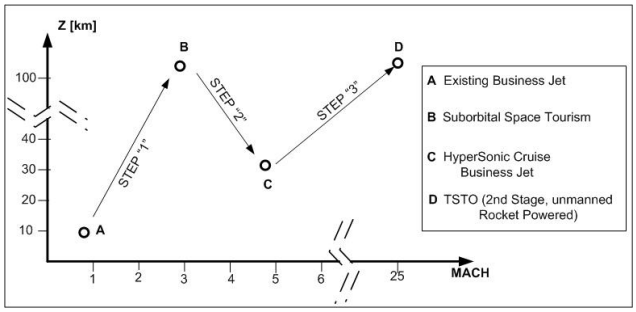


Figure 23. Roadmap for Hypersonic Flight Development.

STEP 1 is fundamental to build an airplane which is a valuable finished product and a good basis for further

developments and at the same time requires limited financial investment. The logical process at the base of STEP 1 is summarized in Figure 23, showing how the rationality of the product is pursued with a critical analysis of current products closer to being realized and the reduction of development costs is ensured by the decision not to develop an original configuration for the application, as it was the case referred to [6], but it is considered the adaptation of an existingsubsonic "Business Jet" (as shown in Figure 22). Please note that such a choice is not a novelty (see e.g. the project "SabreRocket" in Figure 15) and the fact that keeping the original subsonic engines, of the turbofan type (see also project EADS-Astrium referred to Figure 21), ensures high levels of environmental compatibility and safety, in particular the return. Moreover, the assumed configuration provides an excellent foundation for the next STEPS 2 and 3 as shown schematically (together with STEP 1), in Figure 24.

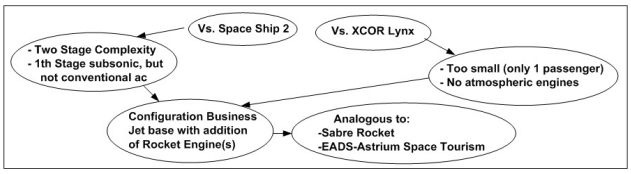


Figure 24. Proposed Roadmap STEP 1.

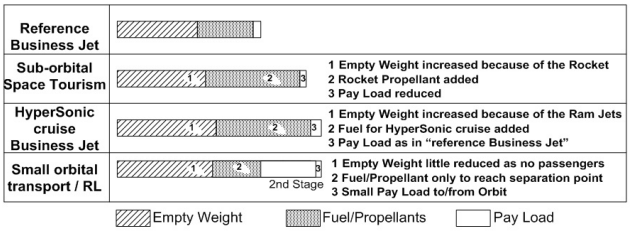


Figure 25. Proposed Roadmap, STEPS 1, 2, 3.

In particular in Figure 24 we can see how, from an existing business jet (total weight, e.g. about 19000 kg) it can be hypothesized to derive, with the addition of a suitable rocket engine, a suborbital space tourism, competitive if compared to aboveseen next projects. The same aircraft then, with the addition of the Ramjet, could become an interesting hypersonic business jet, the most commercially advantageous likelihood as a passenger transport. The same aircraft, giving up considerable part of the fuel, could lead then a 2nd stage that could bring into orbit payload of about 500 kg.

The proposed Roadmap may appear quite obvious but its simplicity can provide guarantees and credibility for any further and deeper consideration towards the Hypersonic Flight development.

A concluding remark can be that STEP 1 and STEP 2 vehicles can easily represent in a not so far future the new products of present general aviation sector. Alternatively, we can say that these aircraft will constitute the future of the general aviation.

6. Conclusions

A synthetic summary of the evolution of hypersonic systems has been presented, showing the immense importance played by X-15 programme in the understanding of the physical phenomena associated with the very high speed flight.

Today, after 50 years, it is still difficult and not yet mature to realize operational vehicles able to reach speed as high as Mach 5 and more. However, the opening of the Space Tourism era is demonstrating the appropriateness of the new approaches proposed in recent years [10] based on the idea to bringing more aeronautics in the game: a closer aeronautics and space view. Evolving this idea and looking forward, it is the belief of the senior authors that the conditions to define a new road map are now mature. Such road map is presented aiming at the development of a TSTO spaceplane by passing through the intermediate steps of Suborbital Space Tourism planes (near to be a reality today) and next Hypersonic Business Jet.

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