

Design of the Scramjet Hypersonic Experimental Vehicle

*S. Di Benedetto¹, M. Marini¹, P. Roncioni¹, A. Vitale¹, F. Battista¹, P. Vernillo¹
S. Cardone²
M. Albano³, R. Bertacin³*

Abstract

In the frame of the research and experimentation for hypersonic flight, the Italian Aerospace Research Centre (CIRA), by means of the national program PRORA, and the Italian Aerospace Agency (ASI), funded a project aimed at designing a propelled hypersonic demonstrator, the Scramjet Hypersonic Experimental Vehicle (SHEV), and its flight experimental mission.

The paper presents the main achievements in designing both the air-launched mission and the flight demonstrator.

The mission scenario foresees the use of a carrier aircraft and a launch vehicle (LV) propelled by a booster to drive the scramjet demonstrator at the defined experimental window. Once released, the hypersonic demonstrator shall be capable of ensuring a controlled and levelled flight at Mach number between 6 and 8, at an altitude ranging from 27 to 32 km, for 10 seconds with scramjet propulsive system on.

This paper describes the more recent activities performed at system level for the vehicle and mission definition and design, identifies the critical technologies and presents the test campaigns planned to achieve the maturity level required at subsystem level; in particular, a dedicated experimental firing test campaign is planned to be performed in the DLR M11 facility in a direct-connect configuration, with the aim at demonstrating the scramjet engine capability to sustain the combustion under aerothermal flight conditions, and the numerical methodology used to perform the combustion analyses and so to assess the aero-propulsive balance.

Keywords: *hypersonic vehicle, flight mechanics, scramjet, trajectory optimization, trim-ability*

Nomenclature

C_{lp} – damping moment derivative
 $C_{L\alpha}$ – lift coefficient derivative
 $C_{m\alpha}$ – pitching moment coefficient derivative
 $C_{n\beta}$ – yawing moment coefficient derivative
CFD – Computational Fluid Dynamics
CHT – Conjugate Heat Transfer
CoG – Centre of Gravity
DoF – Degree of Freedom
GNC – Guidance, Navigation and Control
 I_x – moment of inertia about longitudinal axis
 J – objective function
 L – rolling moment
 L_p – damping rolling moment
 L_o – driving rolling moment
LV – Launch Vehicle

M – Mach number
MAC – Mean Aerodynamic Chord
 M_y – total pitching moment
PDR – Preliminary Design Review
PRORA – Aerospace Research Program
SHEV – Scramjet Hypersonic Experimental Vehicle
SM – Static Margin
SSC – Second Stage Combustor
 T – thrust
 h – altitude
 t – time
 p – roll rate
 $\dot{p}$ – roll acceleration
 x – state vector

¹ Italian Aerospace Research Centre (CIRA), Via Maiorise 81043, Capua (CE), Italy, s.dibenedetto@cira.it, m.marini@cira.it, p.roncioni@cira.it, a.vitale@cira.it, f.battista@cira.it, p.vernillo@cira.it

² Tecnosistem Engineering & Technology, 80133, Napoli, Italy, scardone@tecnosistemspa.it

³ ASI, Italian Space Agency, 00133 Rome, Italy, marta.albano@asi.it, roberto.bertacin@asi.it

α – angle of attack
 β – angle of sideslip
 δ_e – elevon deflection
 δ_T – thrust deflection

Φ – roll angle
 ψ – track angle
 γ – flight path angle
 σ – bank angle

1. Introduction

The last decade has seen increasing attention to the topic of hypersonic flight, both for civil and military applications, with an increase in initiatives dedicated to the development of technologies and related demonstrators.

On this topic, CIRA launched, in 2020, the SPACE IPERSONICA-TEC 662 project [1], funded by the National Program on Aerospace Research PRORA through Ministerial Decree 662, and co-financed, for the first years of development up to the PDR, by the Italian Space Agency. The project, which is part of the research on hypersonic flight experimentation, taking advantage from CIRA strong involvement in the European project HEXAFLY-INT [2] (flight test of an unpropelled vehicle for hypersonic flight), and previously in HEXAFLY [3], aims to develop and test in flight, through a propelled demonstrator, named SHEV, the enabling technologies for future high-speed transport systems.

By taking into account the international scenario, the following system and mission high-level objectives have been defined for the propelled hypersonic aircraft:

- Aircraft class: length 3÷8 m, mass 600÷2000 kg;
- Hypersonic flight at Mach=6÷8, constant altitude 27÷32 km, stable and trimmed;
- Aero-propulsive balance with an aerodynamic efficiency $L/D=3\div4$;
- Scramjet propulsion system with hydrogen as fuel, running steadily for at least 10 seconds;
- Air-launched solution by a subsonic carrier and a rocket-based launch system.

Among the core technologies identified for the development of the hypersonic aircraft, the following have been identified as key technologies to strengthen Italian know-how and capability: the scramjet propulsion system, the use of artificial intelligence for navigation, control, and data processing and high-temperature materials [4].

Concerning the latter point, CIRA has developed in recent years, in collaboration with another Italian company (Petroceramics), an innovative ceramic material, ISiComp®, that is the basis of the thermal protection system that CIRA is developing for the first reusable European spacecraft, Space Rider.

The same material is also used on the hypersonic aircraft, in certain regions with very sharp edges and for certain engine parts. For example, we are using them in the design of our hypersonic propulsion demonstrator.

Particular attention is paid to ground testing activities, which include, as described in the dedicated section, wind tunnel testing for aerodynamics and aerothermodynamics, and testing for the scramjet combustion chamber. This latter activity is particularly challenging, both for the test design, which requires modifying the test bench to correctly reproduce flight conditions, and for the design of the test articles [4].

Finally, some considerations must be made regarding the launch phase, which has been analyzed in terms of feasibility and the preliminary concept of the launch vehicle, but which will require the activation of national or international industrial collaborations to reach the subsequent design phase.

2. Mission and system definition

2.1. Mission scenario

The mission concept envisages an air-launched solution with a carrier (stage I) capable of releasing the payload, composed by the hypersonic demonstrator and an aerodynamically controlled launch vehicle equipped with a booster, at a target point (Sep1) in terms of speed and altitude, then the launch vehicle accelerates until it reaches the foreseen trajectory target point (Sep2) where the hypersonic propelled demonstrator is separated from the launch vehicle and the scramjet turns on and operates for at least

10 seconds (i.e., the experimental window). In this time frame, the demonstrator is supposed to perform a hypersonic flight at constant altitude, guaranteeing a positive aero-propulsive balance and aerodynamic efficiency in the range $3 \div 4$. Finally, the scramjet shuts off, and the demonstrator glides decelerating until the vehicle becomes uncontrollable and splashes down.

The separation conditions are listed in Table 1; the mission is graphically described in Fig 1.

Table 1. Separation conditions

Separation	Altitude [Km]	Mach
Sep1	$13.5 \div 15$	0.6
Sep2	$27 \div 32$	$6 \div 8$

Note that it is assumed that the carrier aircraft returns back and lands at the airport, whilst both the launch vehicle and the hypersonic propelled demonstrator are disposable vehicles, thus they are not recovered.

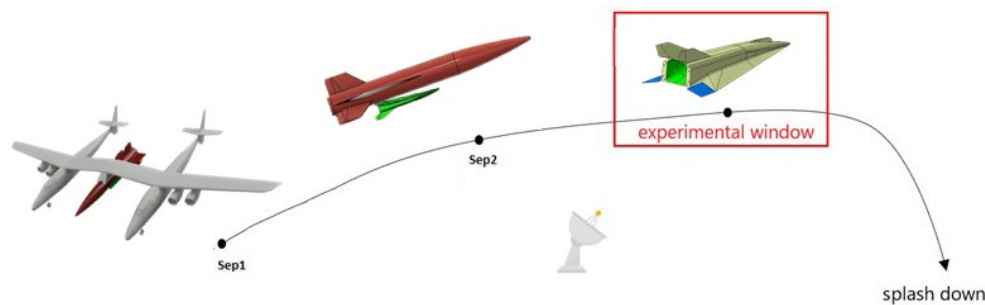


Fig 1. Graphical representation of the experimental mission scenario.

2.2. System configuration

The scramjet configuration studied starts from the results of the EU-FP7 HEXAFLY project [3] opportunely modified to meet the specific project objectives, thus leading to the configuration depicted in Fig 2, with the following main features:

- $L=4.5$ m, $W=1.76$ m
- Mass $1000 \div 1200$ kg

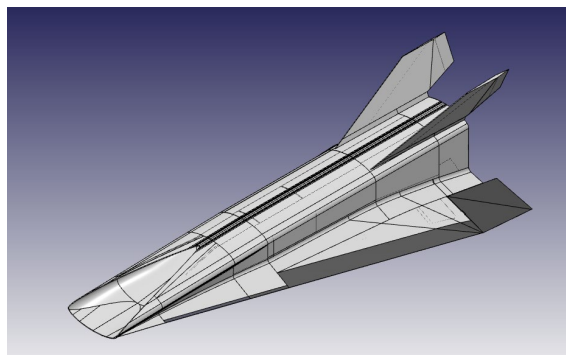


Fig 2. SHEV external configuration

The following main subsystems have been preliminary designed:

- the Scramjet propulsion system with its auxiliaries (see Fig 3);
- the SHEV aerostructure with the proper material layout;
- the Avionics architecture;
- the In-Flight Measurement (IFM) system.

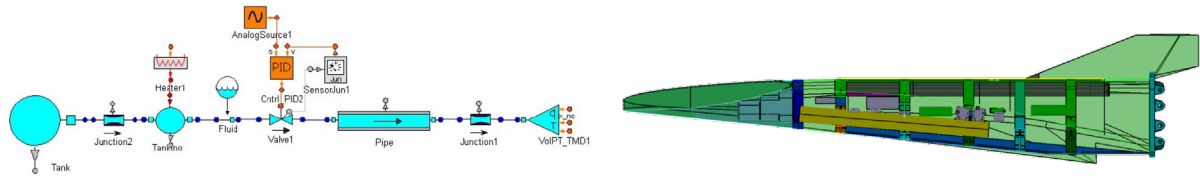


Fig 3. SHEV propulsion subsystem: EcosimPro schematic of the hydrogen fuel system (left) and Preliminary arrangement of fuel tanks into SHEV demonstrator (right)

The complexity of the structure is strictly related to the fuel tanks allocation and the presence of the integrated combustion chamber. These two main elements, that obviously reduce the room available inside the vehicle, together with the high temperature reached during the mission, make the design very challenging. Based on the main requirements and the preliminary information, the structural configuration has been defined by means of a build-up approach. The different structural elements, mainly frame panels and spars assembled, composed of different materials as indicated in the following, are shown in Fig 4.

The structure is mainly composed by milling frames, upper beams and panels. The assembly of fuselage structure is realized by joining upper beams, upper frames and lower frame with fixed bolts, the upper panels are joined to the frames and upper beams by removable bolts in order to allow the access inside of the fuselage for the installation of internal equipment (see Fig 5).

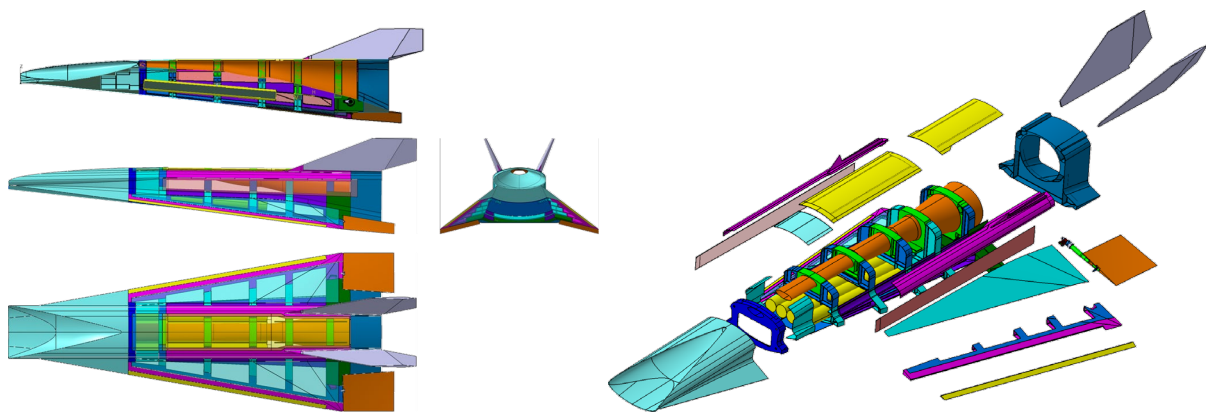


Fig 4. SHEV main structural elements

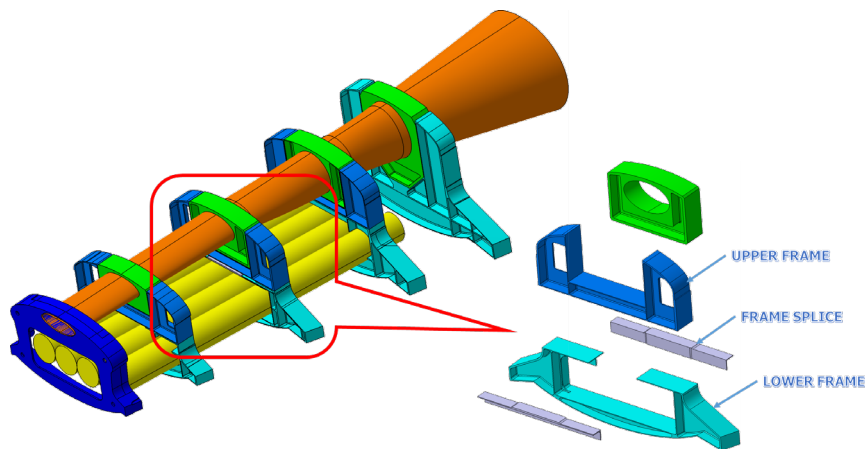


Fig 5. SHEV Structural Configuration

The scramjet combustor has an elliptical shape with a cross-section that progressively expands along its length. Hydrogen gas is used as fuel and is injected through two semi-struts located at the beginning of the combustor, supplying 65% of the total fuel mass flow rate, and a full-strut nearly at mid of the combustor for the remaining 35%, see the figure below.

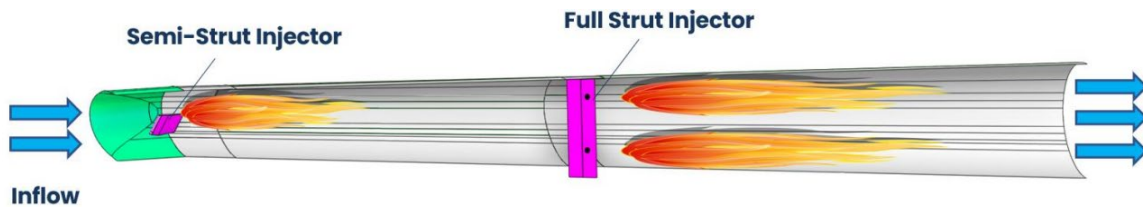


Fig 6. Scramjet combustor internal configuration.

The demonstrator is equipped with its own avionic and in-flight measurement system, whose definition is ongoing. The main avionic subsystems are: Power Management System, Flight Control Computer (FCC), In-flight measurement system (IFMS), servo-actuator and Pyro Control (ACU, PYRO), Telemetry and Telecommand (TT&C), Scramjet Control Unit. The avionic functional diagram is shown in Fig 7.

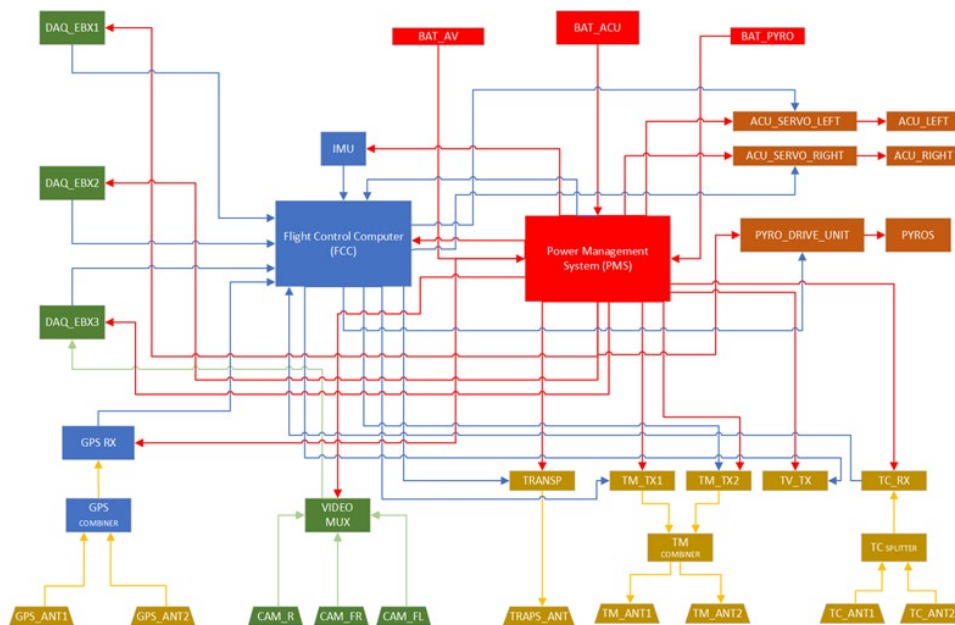


Fig 7. SHEV avionics functional diagram

Several configurations of the system composed by launch vehicle and flight demonstrator have been examined with the aim to guarantee high aerodynamic efficiency and low structural loads, and to simplify the structural interface between the launch vehicle and the SHEV, in order to reduce integration complexity and separation's risks when the SHEV is released.

Two main structural configurations were analysed, one where the SHEV and launch vehicle are mounted in line and another where the SHEV is positioned under the launch vehicle (see Fig 8). For these two configurations, different solutions for joint SHEV and launch vehicle have been evaluated with different types of fixing. The feasibility studies have been supported by preliminary stress analysis calculation, which identified as most promising configuration the one in which the experimental vehicle is fixed upside down under the launch vehicle.

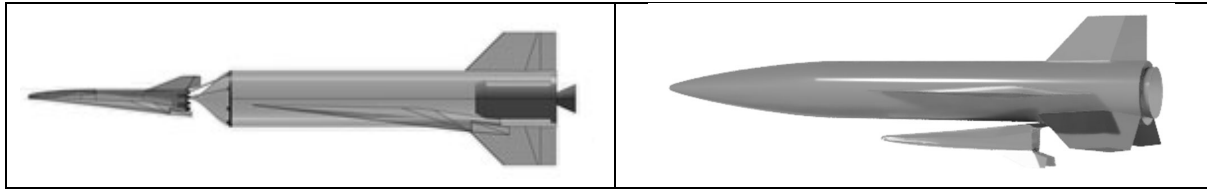


Fig 8. Examined structural configurations of the payload: SHEV and launch vehicle in line (left) and SHEV under launch vehicle (right)

3. Launch System Design and Optimization for SHEV

The Launch Vehicle (LV) developed for the Scramjet Hypersonic Experimental Vehicle (SHEV) underwent significant redesign and optimization to address critical aerodynamic, structural, and interface challenges identified in the initial configuration [5].

It is worth to remind that the booster equipping the Launch Vehicle has been refurbished starting from a booster from the Northrop Grumman ORION family [1][4].

The initial LV design (Fig 9) exhibited excessive aerodynamic loads during transonic ascent and complex structural interfaces, mainly due to the forward positioning of the SHEV. This configuration resulted in large bending moments at the interface, requiring multiple structural rods and additional wedges at the interface with the SHEV. Such complexity not only complicated the separation process but also left residual interface components attached to the SHEV during the hypersonic experimental flight, thereby significantly increasing aerodynamic drag and consequently reducing the effective duration of the experimental hypersonic flight phase.

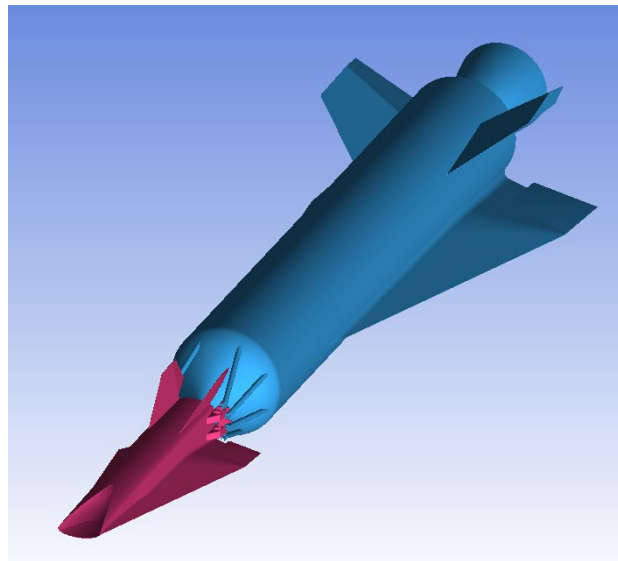


Fig 9. Initial LV design

To resolve these critical issues, the SHEV was repositioned beneath the LV (Fig 10). This significant structural modification drastically reduced the bending moments acting on the interface by shortening the effective moment arm, simplifying the mechanical interface design (Fig 11). The new interface can now remain entirely on the LV after separation, eliminating any residual components on the experimental vehicle. Furthermore, repositioning the SHEV below the LV allowed for a more elongated and aerodynamic nose profile for the launcher. This redesign effectively has weakened the shock wave generated ahead of the LV, enhancing aerodynamic efficiency and overall performance.



Fig 10. Improved LV configuration

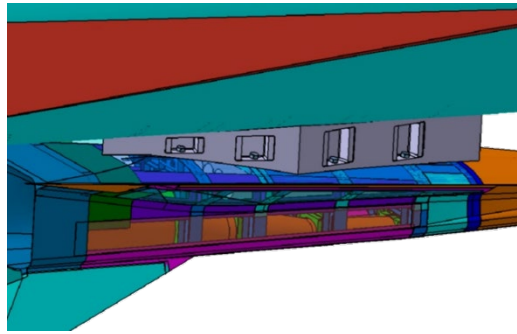


Fig 11. Diamond shape interface fixed with pyrobolts

Eulerian CFD simulations of launch vehicle improved configuration have confirmed these aerodynamic improvements, demonstrating notable reductions in aerodynamic drag and substantial gains in aerodynamic efficiency, with improvements up to threefold at higher Mach numbers compared to the initial configuration (example at $AoA = 4^\circ$ varying Mach number in Fig 12). These aerodynamic enhancements directly translate into improved mission performance, optimized fuel consumption, and potentially better flight conditions for reaching the experimental window.

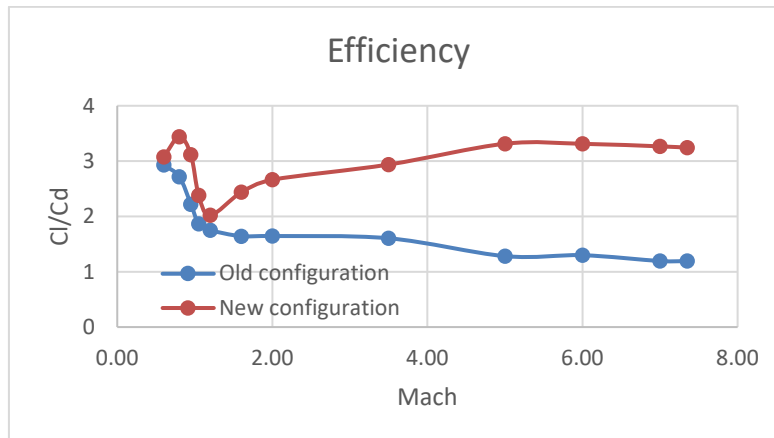


Fig 12. Comparison of aerodynamic efficiency between old and new configurations, for $AoA = 4^\circ$ with varying Mach number

Comprehensive longitudinal trimmability analyses (Fig 13) of Payload flight mission (from Sep1 to Sep2), conducted by prescribing an optimized analytical Flight Path Angle (FPA) profile, confirmed the availability of stable trim conditions throughout the ascent trajectory. Evaluations of structural loads at the SHEV's CoG indicated significant reductions compared to the original configuration, confirming manageable and safe structural requirements for the interface design.

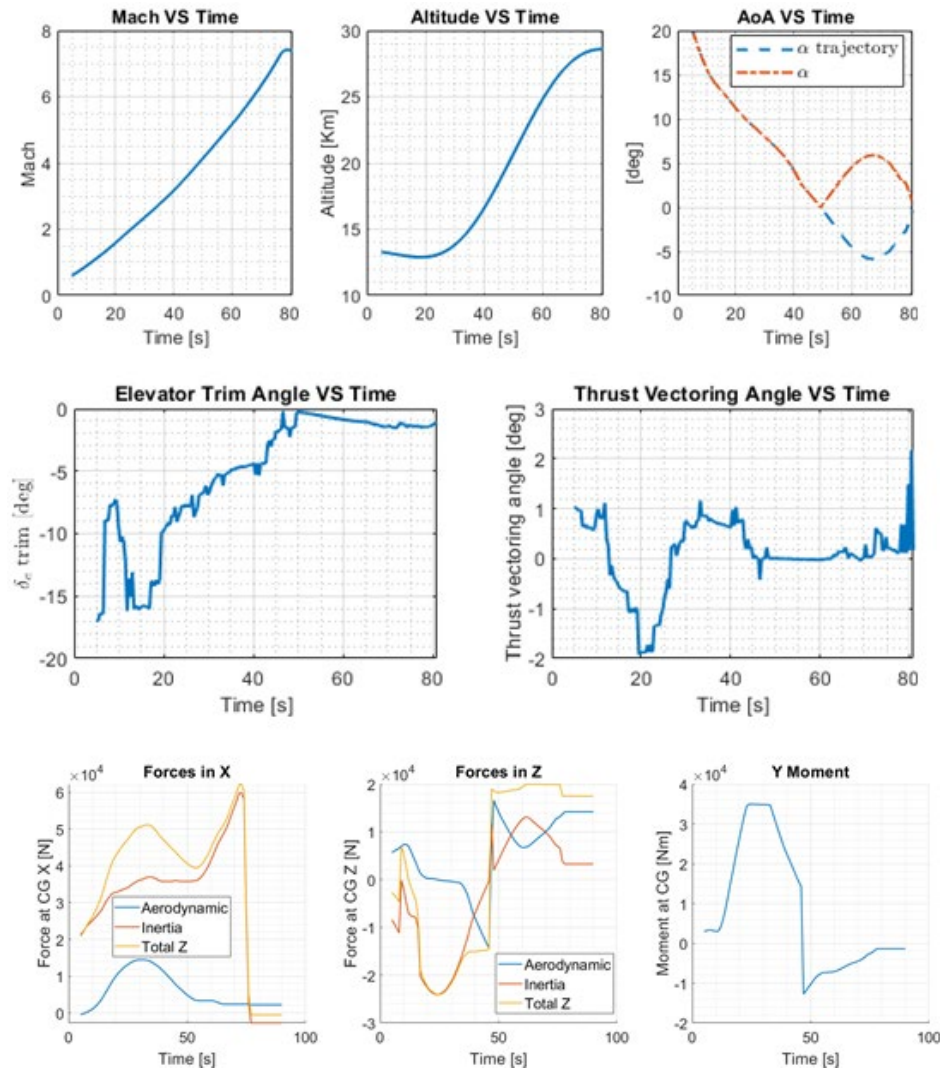


Fig 13. LV Flight mission: longitudinal trimmability analyses results

Additionally, lateral-directional stability analyses showed acceptable stability characteristics, though the timing and dynamics of the roll maneuver of the Launch Vehicle with the SHEV mounted beneath (required to reposition the SHEV from its inverted ascent position to an upright orientation) remain critical aspects. Detailed ongoing analyses aim to determine the optimal maneuver timing and configuration to ensure safe and effective separation and minimize associated stability risks.

Future work to further enhance system robustness of the improved Payload configuration includes conducting detailed viscous CFD simulations to better characterize aerodynamic and aerothermodynamic behaviors, full 6-DoF flight mechanics simulations incorporating dynamic vehicle response and control surface actuators behaviors, optimization studies for the roll maneuver, and structural validations of the mechanical interface design.

4. Payload Flight Mechanics

Flight mechanics analyses aimed to assess the payload flying qualities (longitudinal trim and static stability) and to define its nominal trajectory (from Sep1 to Sep2). The analyses have examined the most promising configuration, that is, the one with the SHEV beneath the launch vehicle; therefore, the nominal trajectory shall include a roll manoeuvre needed to set the SHEV to the experimental window with the required attitude [6].

The trim problem is solved on the whole mission flight envelope and presents two peculiarities: the

management of the control allocation between elevons deflection and thrust vectoring angle, and the time varying thrust contribution to the pitching moment along the trajectory. The former is handled by maximizing the thrust vectoring contribution before using the elevons deflection, thus minimizing the latter. This choice allows exploiting the remaining available elevons deflection angle for manoeuvring purpose. The envelope analysis is carried out considering the minimum value of the thrust (available at the rocket switch on) and a nominal thrust deflection angle needed to trim; along the trajectory, the actual value of the thrust vectoring angle is computed by solving the equation in which the pitching moment due to the initial thrust and related nominal trim angle is equated to the moment due to actual thrust and actual thrust vectoring trim angle. Since the actual thrust is always bigger than the initial one, the module of the actual thrust vectoring angle will result lower than the nominal one. Trim results are defined for each combination of Mach number, angle of attack, altitude, and centre of gravity (CoG) position, and are shown in Fig 14 for different combinations of the four governing variables. The effect of altitude results less significant than that of the CoG, with improved trim margins when the CoG is located closer to the tail of the vehicle. The most challenging region for achieving trim is consistently found in the transonic regime.

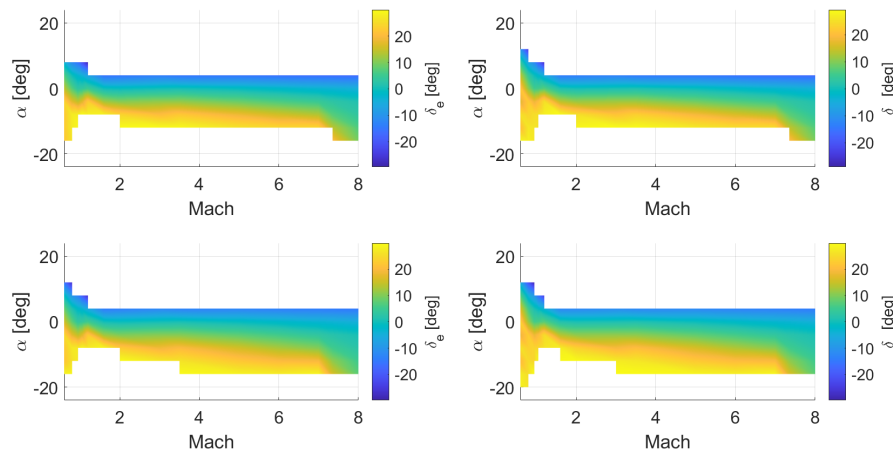


Fig 14. Launch vehicle elevons' deflections in Mach – α plane: low altitude, forward CoG (left up); high altitude, forward CoG (right up); low altitude, aft CoG (left down); high altitude, aft CoG (right down)

The definition of the nominal trajectory consists in computing the guidance law of the vehicle, which for a longitudinal mission coincides with the angle of attack profile. Next, this profile is used as input to a simulation model to obtain the time histories of the vehicle's state vector and all the parameters that are relevant for mission analysis. The computation of the guidance law requires the solution of a nonlinear constrained optimization problem, where the objective function is defined as the error according to some metrics with respect to the flight conditions identifying the experimental window of the SHEV, and the constraints derive from the other mission and system requirements. The nominal trajectory shall also take into account the effects in and out of the longitudinal plane of the roll manoeuvre, which is pre-computed using a simplified decoupled model and used as input to the trajectory calculation. Three nominal trajectories have been computed, mainly differing for the flight conditions in which the roll manoeuvre is executed (soon after the release from the carrier, just before the SHEV release, and in an intermediate point of the system trajectory). Static stability has been assessed through the evaluation of pitch stiffness and static margin along the whole trajectories, whereas directional stability has been measured in the flight conditions in which the roll manoeuvre is executed. The computed nominal trajectories have resulted compliant to mission requirements, longitudinal and directional stable, except for the first one (roll manoeuvre executed soon after the release from the carrier) which exhibits a slightly unstable longitudinal configuration precisely during the roll manoeuvre and requires an elevons deflection to trim and manoeuvre which exceeds the allowable range. However, it is worthy to note that the control system used to compute the roll manoeuvre was not optimized and some improvement margins exists. One of the obtained nominal trajectories is shown in the following figures. Finally, the flight mechanics analyses have allowed dimensioning the booster, by computing the minimum thrust required to achieve the mission objectives.

In general, the obtained results have provided useful information concerning mission definition and have confirmed the feasibility of the flight test.

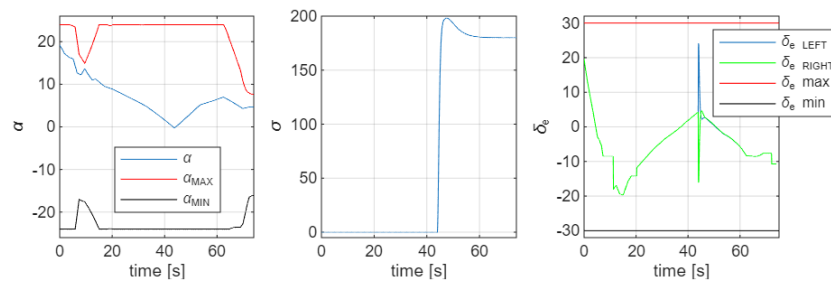


Fig 15. Payload nominal trajectory for intermediate roll manoeuvre: angle of attack (left), bank angle (middle), elevons deflection (right)

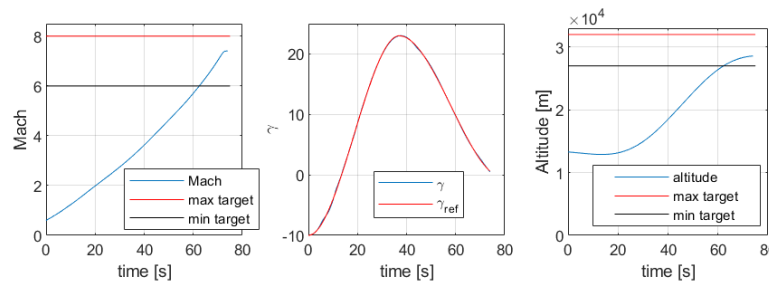


Fig 16. Payload nominal trajectory for intermediate roll manoeuvre: Mach number (left), flight path angle (middle), altitude (right)

5. Experimental plan

Several experimental test campaigns are foreseen in the project to support the activities of design, development and related validation. In particular, the tests can be grouped in:

1. test campaigns in experimental facilities with different models, in order to support the design of the hypersonic propelled demonstrator in the fields of aerodynamics, aerothermodynamics and propulsion, with a focused study on supersonic combustion;
2. tests at sub-system and/or system level (functional, environmental, etc.) for avionics, GNC, telemetry, on-board sensing equipment, propulsive system, actuation lane of control surfaces, etc;
3. tests for the fully integrated demonstrator (mass, inertia and center of gravity); ground vibration tests; sample functional tests of the sub-systems; tests of connections with the launch system; release tests; etc.

Activities are currently ongoing to design test campaigns and models related to point 1 of the previous list; some results related to the preparation of the supersonic combustion test are provided in the following sections, as well as some first reasoning about aerodynamic and aerothermodynamic tests.

5.1. SHEV Scramjet combustor experimental test

A key part of the project is an experimental test campaign for the scramjet combustor at the DLR M11.1 facility. Initial simulations, however, revealed a critical limitation: the facility's maximum total temperature of 1500 K is not sufficient for the air-hydrogen mixture to achieve auto-ignition and sustain stable combustion.

To overcome this issue, CIRA has designed an additional component [7]: a Second Stage Combustor (SSC) whose purpose is to increase the flow total temperature to 2000 K, a necessary condition for scramjet combustion. Two SSC configurations have been studied: a reference design with three injectors and a restriction, and an alternative design with four injectors and no restriction. The

alternative design has been developed to reduce thermal stress on the walls but resulted in a lower temperature homogenization at the outlet. Moreover, a Nozzle Adapter was designed as critical interface, connecting the circular, subsonic SSC outlet to the elliptical, supersonic scramjet combustor inlet.

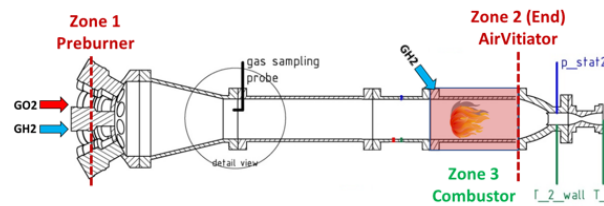


Fig 17. Facility DLR update with second stage combustor (Zone 3)

Extensive Computational Fluid Dynamics (CFD) simulations were conducted using ANSYS-FLUENT®. The analyses were focused on the integrated system of the nozzle adapter and scramjet combustor, using inlet conditions from both SSC designs.

The simulations have demonstrated that, despite the differences in outlet homogeneity between the two SSC configurations, the nozzle adapter effectively homogenizes the flow. This finding validated the use of the alternative SSC design, which offers better thermal reliability without compromising downstream performance.

Furthermore, the analysis showed that the pre-combustion in the SSC creates a "vitiated air" mixture, leading to a fuel-rich mixture (global equivalence ratio of 1.3) in the scramjet combustor, a deviation from the nominal flight condition ($ER=1$). This shift in mixture composition affects the flame position, which impinges on a specific part of the combustor wall.

Both the nozzle adapter and the scramjet combustor are subjected to intense heat fluxes and, by a first analysis, require active cooling systems. Conjugate Heat Transfer (CHT) simulations were performed to design and validate these systems.

The preliminary Nozzle Adapter cooling system consists of 32 circular, water-cooled micro-channels with a 5 mm diameter, embedded in the 10 mm thick walls. The channels bifurcate to optimize coolant distribution (see Fig 20 – left). Simulations showed a maximum internal wall temperature of approximately 470 K, well below the material limit.

Similarly, the scramjet combustor features a cooling system with 64 straight, 5 mm diameter channels within its 10 mm thick walls (Fig 20 – right). CHT simulations confirmed that this system maintains the maximum internal wall temperature at a safe level of about 480 K, even in areas with localized high heat flux caused by flame impingement.

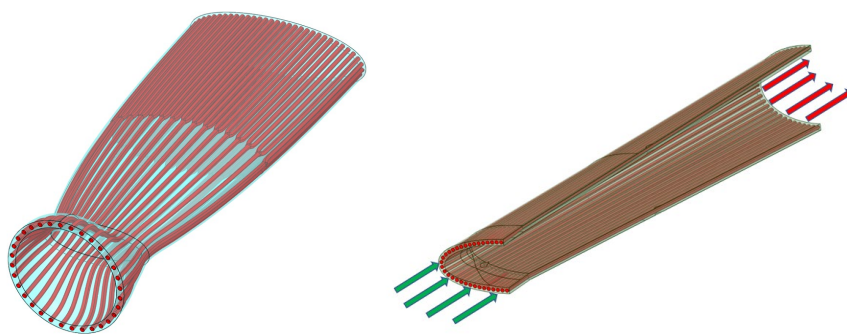


Fig 18. Cooling systems design: nozzle adapter (left) and scramjet combustor (right)

The numerical analyses have shown that the SSC and nozzle adapter are essential for enabling ground tests of the SHEV scramjet combustor at the DLR facility. The simulations successfully validated the functionality of the integrated system and confirmed that the designed cooling systems are robust enough to manage the extreme thermal loads.

The next crucial step is the experimental test campaign, which will provide real-world data to validate and refine the CFD models. This will be a fundamental step toward the future development of the SHEV vehicle.

5.2. SHEV aerodynamic and aerothermal tests

The aerodynamic tests will be aimed to characterize the aerodynamic forces and moments acting on the SHEV in the whole flight envelope (in motor-off conditions) to complete the aerodynamic database [1][4], and to study the start/unstart phenomenon of the air intake. The SHEV flight envelope in terms of Mach and Reynolds numbers is reported in Fig 21, with the reproduction capabilities of some European wind tunnels. The combined use of DLR-TMK ($M=2\div4.5$) and DLR-H2K ($M=5.3\div7.05$) could be an optimal solution with a model length of $0.5\div0.6\text{m}$.

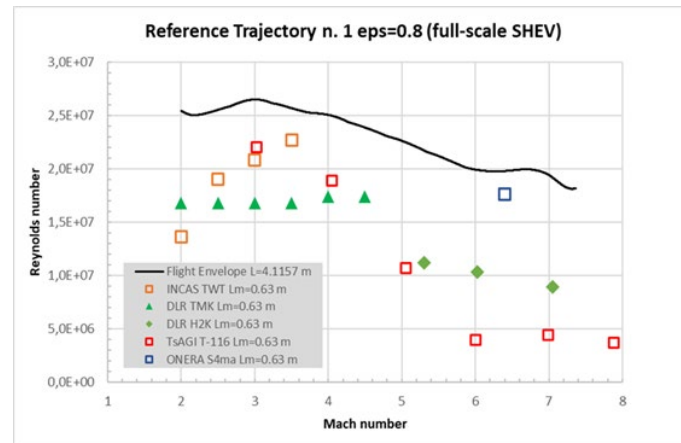


Fig 19. Ma-Re flight envelope and wind tunnels coverage

Aerothermal tests for materials assessment could be performed on three representative models (blunted flat plate, wedges) of the most critical parts of SHEV (i.e., leading edge of intake, wing and vertical tail) with the possibility of using different TPS materials (e.g., CMC). The tests will be designed to reproduce the mission thermal load and will qualify the materials identified for the present high-temperature environment. These tests could be performed in the CIRA plasma wind tunnel "Scirocco".

6. Conclusions

This paper presents a summary of the more recent results achieved within the CIRA-ASI project on hypersonic flight, in preparation of the project Preliminary Design Review, with the final goal of designing a hypersonic propelled demonstrator to increase the Technology Readiness Level of both system and technologies for future hypersonic transport vehicles.

First system activities, such as demonstrator configuration, mission scenario definition, payload flight mechanics and SHEV main subsystems design have been described in the paper, with a focus on the main critical technologies to be developed and on the ground experimental plan, that foresees, among the others, a challenging test of the scramjet combustion in real flight conditions.

Acknowledgements

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