DOI: 10.13009/EUCASS2017-408

From MDO to detailed design of Hypersonic Morphing Cabin Escape Systems

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Abstract
HYPMOCES (Hypersonic Morphing for a Cabin Escape System, http://hypmoces.deimos-space.com/) is an EU FP7 funded project, coordinated by DEIMOS Space, which aims to investigate and develop technologies in the area of control, structures, aerothermodynamics, mission and system required to enable the use of morphing in escape systems for future hypersonic transport aircrafts.
This paper describes the overall concept and organisation of HYPMOCES and gives a summary of the results obtained, covering the main design steps: Multidisciplinary Design Optimisation and Detailed Design. From the results obtained and from the challenges faced, multiple areas of interest emerged as potential topics for future investigations.

1. Introduction

Passenger safety is one of the main drivers for the development of future trans-atmospheric transportation systems. The high levels of energy associated hypersonic flights as well as the level of reliability of the enabling technology leads to the need of a passenger escape system in case of flight abort.
The main goal of HYPMOCES (HYPersonic MOrphing system for a Cabin Escape System, an EU FP7-funded project, coordinated by DEIMOS Space) is to investigate and develop the technologies in the area of control, structures, aerothermodynamics, mission and system required to enable the use of morphing in escape systems for hypersonic transport aircrafts.
Cabin Escape System, Morphing and Hypersonic Flight are the three pillars over which the HYPMOCES project is built: an introduction is given in the following subchapters.

1.3 Cabin Escape Systems

Cabin Escape Systems have been conceived, studied, designed, tested and implemented in a wide range of concepts from subsonic up to hypersonic manned vehicles. A subset of key examples is shown in Figure 1, covering one century of historical solutions, ranging from the first ejection seat patent (1916) to the SpaceX Dragon Pad Abort Test (2015) and from subsonic civil aircrafts (patents for escape systems in commercial flights) to space vehicles (design concepts for Space Shuttle Orbiter and Buran). This brief historical perspective highlights the general interest in Cabin Escape Systems and the ultimate goal of improving passengers or crew safety in challenging conditions.
In case of hypersonic flight, escape systems are necessary to cope both with the risk associated to high energy management and the system reliability, mainly for the propulsion. A large cabin escape system able to change its shape and automatically reconfigure during an abort event after ejection will balance the compromise between the constraints for the integration within the mother aircraft (compactness), the adaptability to the unpredicted environment in case of abort and the required flight performance to ensure safe landing.
The implementation of a cabin escape system for a hypersonic aircraft is challenged by the integration within a larger structure, the load factors for the passengers, the ejection propulsion concept, the capability to withstand extreme thermal environment (plasma flow) and the adaptability to a wide range of abort scenario conditions (low and high

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speed and altitude). This multi-phase nature of the return flight makes morphing an attractive solution for a hypersonic escape system. The abort scenarios cover a wide range of flight conditions and the integration within the mother spacecraft requires compact solutions in terms of shape (ex: capsule adapted to outer mold line). Thus a single shape cannot provide adequate performances and consequently it can be challenging (ex: load factors) for the wellness of the ordinary passengers expected in the cabin. The increase of the lifting capability after ejection of an escape capsule and the increase of aerodynamic control surfaces is a strong requirement in order to safely return to ground the crew – composed by non-trained persons.

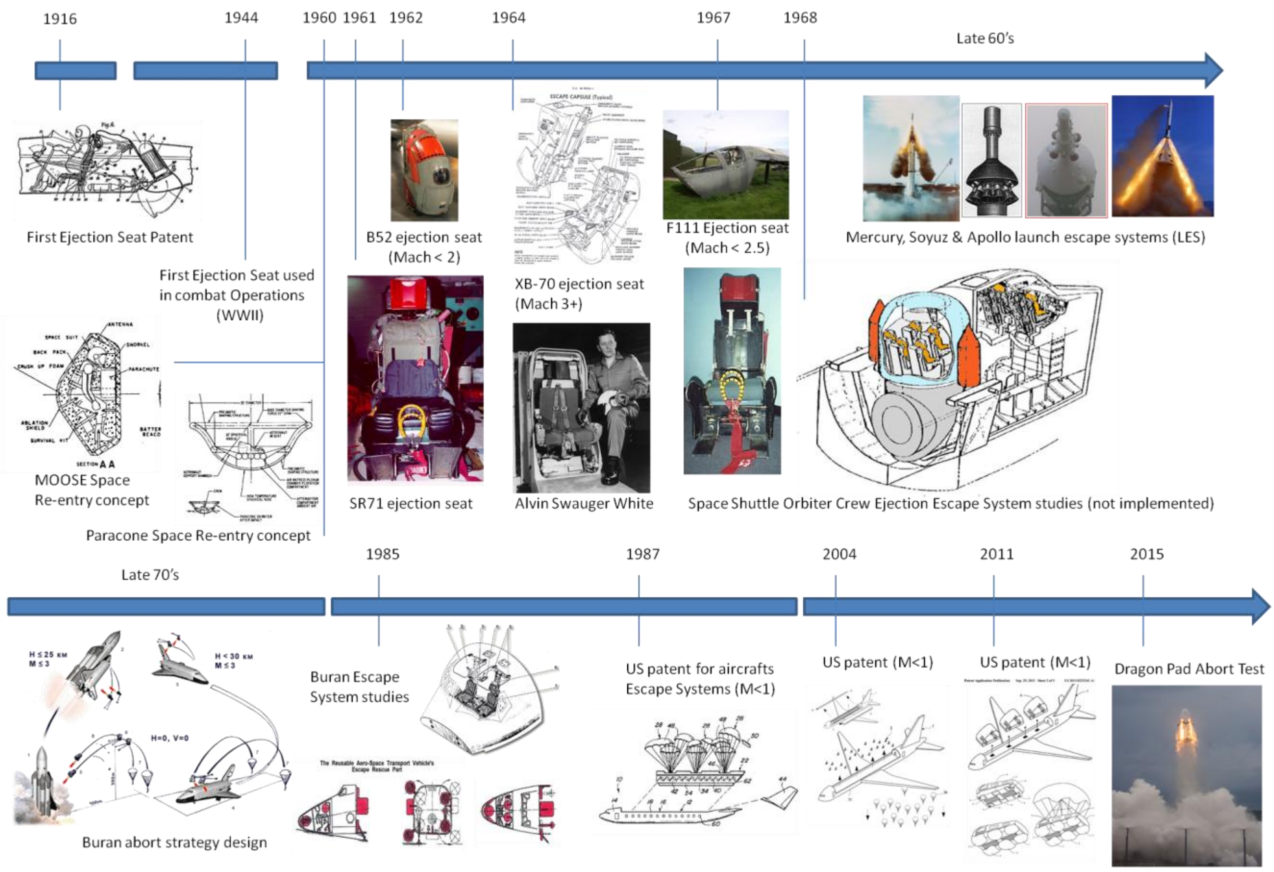

Figure 1: Escape systems, an historical perspective

1.1 Morphing

In general, morphing is the adaptation of a system to a changing environment. Morphing, understood as external shape adaptation is not new in aeronautics and space. In aircrafts, it has been implemented with different levels of complexity: from deployment of high lift surfaces and retractable landing gear to variable sweep or folding wings. The most advanced morphing concepts were implemented in the field of military applications and no practical use in transport aircraft as the increased complexity and operational costs dominated over the improved performances.
In atmospheric space vehicles morphing has been also used to improve performances and to trigger different mission phases: from deployment of hypersonic and subsonic parachutes in entry capsules to folding wings. In suborbital flight, a recent example of morphing is the feathered wing concept implemented in the Space Ship One prototype and flight tested (May 2017) by Virgin Galactic through the Space Ship Two VSS Unity (see Figure 2) flight 08.
At design level, morphing has been widely studied either in aeronautics [1] or space applications as it is an attractive solution aimed to maximise the system performances for multi-mission concepts. In recent years, the development of new materials capable of sustaining extreme environments is enabling new design solutions and the successful number of design and tests of inflatable (IAD) and deployable (DAD) aerodynamic decelerators concepts (Figure 3) is increasing over a wider range of flight conditions [2], [3]. These compact and lightweight concepts are game-changing solutions to achieve cost effective reductions of the ballistic coefficients of challenging Entry Descent and Landing missions, like those designed to land a large payload to Mars [4].
From a controllability perspective, the morphing of the shape of a vehicle triggers a second level of morphing related to the reshape of the onboard flight control system to the changed plant, for instance in terms of trim point.

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Therefore, requirements like the accurate detection and measurement during the shape transition, the adaptation to the new environment and the overall robustness are required to the Guidance, Navigation and Control (GNC) system. Fast morphing transitions and gradual morphing in which the shape adaptation is time varying poses different challenges to the guidance (changing vehicle trajectory capability), Navigation (precise estimation of the actual vehicle state) and Control (changing plant, control means and authority and transient control).
Morphing can be qualified as an ideal solution from an airworthiness standpoint. However, the structural implications have been a common showstopper due to the increased complexity which means cost. Movable structures under high thermomechanical loads have severe implications like the transfer of loads, deformability, aero-elasticity, friction, precision of the operation, mass, volume and power.

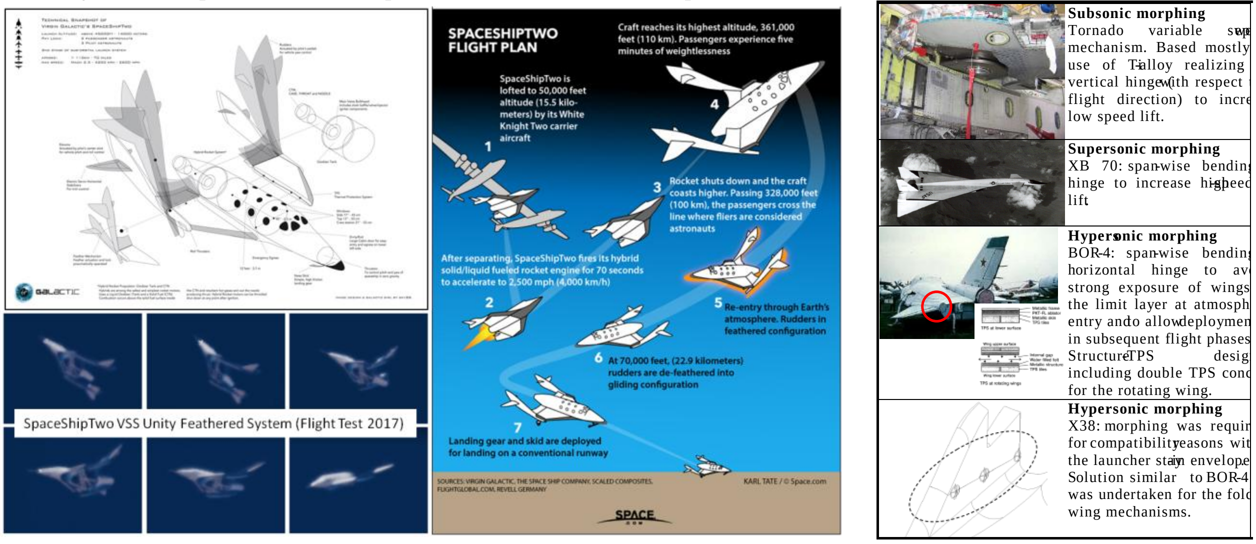

Figure 2: The SpaceShipTwo (left and middle) and selected subsonic to hypersonic morphing concepts (right)

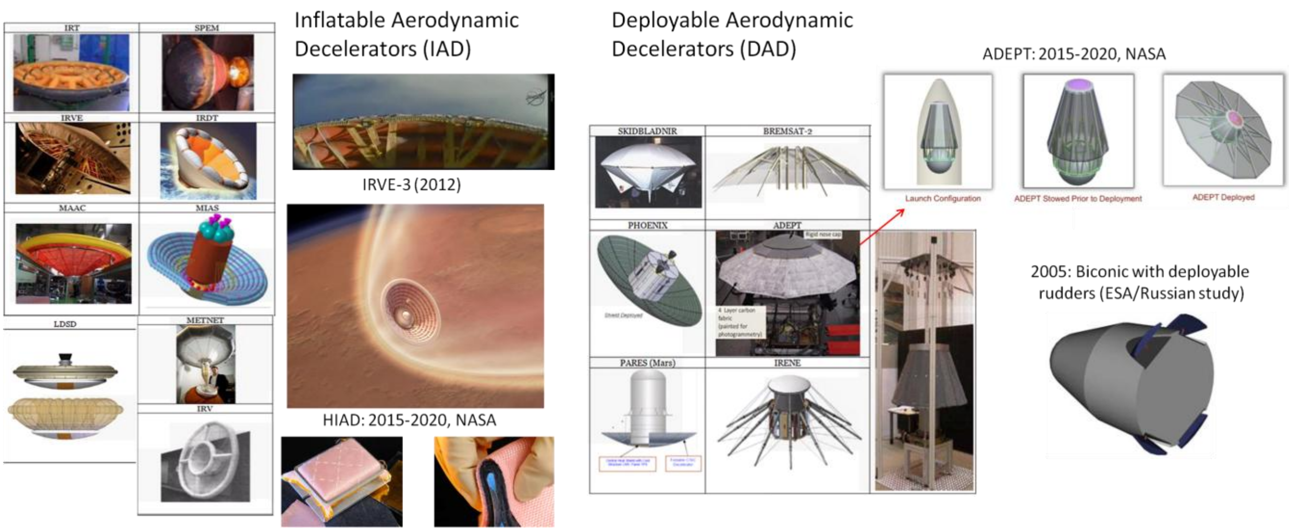

Figure 3: Inflatable (left) and Deployable (right) Aerodynamic Decelerators, a summary of key concepts

1.2 Hypersonic flight

Hypersonic flight is an enabler of trans-atmospheric transportation. Two main branches of concepts have been proposed: propulsive cruise using advanced propulsion technology (ex: SCRAMJET), like NASP or Zero Emission Hyper Sonic Transport [5] or gliding flight from a high-altitude injection like the SpaceLiner [6].
Thus, hypersonic flight deals not only with high levels of energy (speeds between Mach 7 and 20 and altitudes between 30 and 100 km) but also with the need of propulsion systems able to bring the system to the hypersonic cruise speed or to the gliding entry velocity based on rocket technology. Therefore, launch pad abort or abort during ascent must be tackled. For the concepts requiring flight at high speed (beyond Mach 4), the escape systems are also

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deemed necessary during the trans-atmospheric gliding descent. Figure 4 shows where an escape system using morphing should operate and the existing systems in the altitude – Mach domain.
High hypersonic applications are additionally challenged by the extreme environment: where surrounding temperatures can easily exceeded 1500K boundary layer transits from laminar to turbulent increasing heat fluxes and local small geometry “defects” like steps and gaps can change the large scale aerothermodynamic behaviour. In fact, high speed hypersonic flight is characterised by a narrow entry corridor bounded by thermo-mechanical constraints and vehicle flying qualities requiring precise trajectory and attitude control and onboard estimation of the vehicle status and adaptation to the different flight regimes.

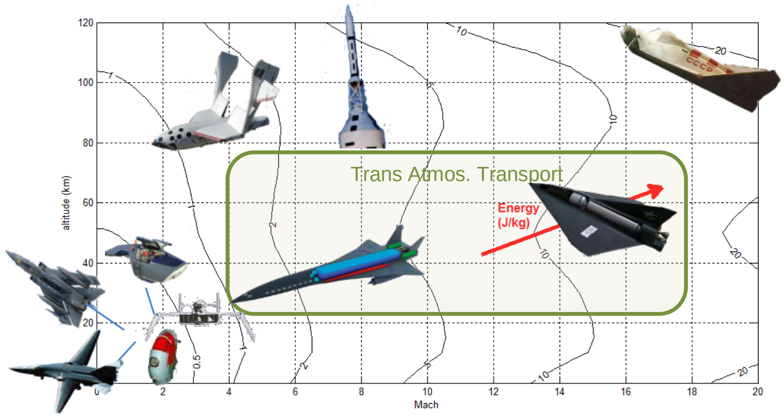

Figure 4: Morphing and escape systems in aerospace and trans-atmospheric transportation envelope

1.4 Objectives

The HYPMOCES project addresses the key technological areas to enable the use of morphing in hypersonic escape systems. In addition to technology, the concept feasibility from a system and mission standpoint is appraised using a high-energy trans-atmospheric transportation system based on the Spaceliner Concept as reference (see ch.2).
This goal and aim are achieved by pursuing four main scientific & technological (S&T) objectives:

1. **Mission and GNC approaches for morphing (DEIMOS Space).**

Morphing is a transitory process where the flight control system (FCS) needs to adapt to a changing plant to ensure right safety margins. Adaptability and robustness are thus key features required for the control system, especially in such demanding and uncertain conditions as those of hypersonic flight at high altitude. In addition, precision in the (gradual and/or rapid) deployment of morphing structures relies on accurate measurement and estimation techniques in order to provide feedback to the flight control system and to the actuators control unit. Therefore, the goal of this objective is to investigate state-of-the-art techniques for real-time adaptation and reconfiguration of the flight control system as well as the estimation techniques required for proper adaptation/reconfiguration. The theories of linear fractional transformation (LFT) and linear parameter varying (LPV) are highlighted as preliminarily identified candidates since both techniques deal with uncertainty and dynamic changes in a system. Indeed, the use of LFT models opens the door for the use of advanced on-line estimation approaches in unison with on-line V&V for the identified model and adapted controller. Adaptive methods for the onboard trajectory re-planner module of the Guidance module are investigated to provide real-time flight corridor reconfiguration.
The mission analysis and flight mechanics define the flight scenario and they are the source of requirements (ex: sizing trajectories, response bandwidths…) for key systems like the GNC, the Thermal Protection System and the structure. The objective is to provide the flight corridor envelope as target for the morphing system performance as well as to investigate the on-board techniques (on-board morphing plant model) required to enable the computation of transient flying qualities during the morphing actuation as input to the on-board trajectory planner and to the attitude control system.

2. **Innovative structural and material solutions (AVIOSPACE).**

An efficient structural solution is investigated to guarantee that the required shape change is performed with precision, with reduced impact on system mass, volume and required power for the mechanism. It encompasses the use of new materials, advanced actuators and mechanisms, structural layouts and load transfer schemes. In case of mechanisms located in areas affected by high thermal load, the feasibility of ceramic hinges (e.g. based onto Zirconia-Yttria) are considered together with their qualification and inspection approach based on the state of the art of ceramic NDI (Non-Destructive Inspection) assessing the feasibility of a ground validation but also of a real-time monitoring of the equipment associated with the relevant impacts at system level in terms of mass and power budget. Another area of potential development consist in the study of highly reliable coating protecting lightweight structures

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from high thermal flux – this kind of application would be applicable for non-reusable solutions and hence for the kind of occurrences in which a safety escape system is used. In this case, particular care shall be devoted to the evaluation of the reliability of the coating after long periods: in fact such a coating would be never used in the nominal life of the spaceplane but would be required of its full performance at worst once in the vehicle lifetime.
The solution undertaken for this kind of coating could consist not into an ablative paint (as the one used for the high-speed missions of the X-15) for reliability on long timeframes but very likely in a spattering of one or several layers having very low thermal conductivity, requiring no inspection during the normal life. All solutions have also to be coupled with the use of thermal capacitors based on phase-change capable of retaining portion of the incoming thermal energy with no temperature increase – also for this provision the adequacy of the present equipments has to be screened and possible enhancements (in terms of base materials to be used) have to be identified.

3. **System integration (DLR).**

Candidate morphing schemes are proposed and traded-off to identify candidate architectures that are compatible with the constraints imposed by the integration within the mother aircraft, not only in terms of the direct impact in mass, volume, power and complexity but also considering the overall operation of the cabin escape system and the mother aircraft. As far as possible the capsule shall be an integral part of the orbiter structure. This imposes the necessity to find the best compromise between the requirements of the capsule and the orbiter. Candidate architectures include the use of morphing solutions like folding wings, sliding surfaces, telescopic wings, deformable shape and tilting wings. From a system perspective, the objective is to tackle the multidisciplinary problem of hypersonic and morphing using an integrated engineering approach. The DLR Concurrent Engineering Facility (CEF) has been used to support the multi-disciplinary analysis effort for the initial trade-off, bundling the competencies of each partner in an interactive process. System requirements for morphing schemes and operational aspects have also been formulated and evaluated.

4. **Aerothermodynamics (ONERA).**

In this project, the aerothermodynamics activity acts as a “numerical laboratory” which develops methodologies specific to the hypersonic morphing topic and perform fine testing during the iterative process which aims to define the best technological choices. Static and transient techniques for aerodynamics and aerothermodynamics characterization during the shape morphing process are applied as input for the system design (thermal protection system), mission and flight mechanics and especially to the GNC system in order to enable the real-time on-board reconfiguration.
Numerical prediction methods focus on the microaerothermodynamics aspects (local gaps, steps) as well as on the transient effects. Starting from the Reynolds-Averaged Navier-Stokes (RANS) formulation for the turbulent flow motion besides chemical equilibrium /non-equilibrium consideration for the species evolution in hypersonics, advanced CFD techniques are addressed to model the shape transition both from an aerodynamics and aerothermodynamics stand-point. It includes the use of unsteady RANS as well as mesh deformation methods allowing for taking into account motions of the morphing structures by identifying the mesh deformation law and the deployment sequence provided by the system designer. In terms of heat fluxes, the change from laminar to turbulent flow heat fluxes is characterized with techniques like the inclusion of artificial roughness to force transition.

1.5 Approach

Morphing, hypersonics and escape systems require a multidisciplinary approach from a system perspective in order to identify candidate architectures not biased by a single discipline leading to an unrealistic design.
The undeployed (before morphing) Cabin Escape System (CES) has been provided as initial concept by DLR as input coming from previous SpaceLiner system studies (see chapter 2), showing challenges and areas for future investigations like the integration within a larger structure, the load factors for the passengers, the propulsion concept and the adaptability of the escape cabin to the different abort scenario conditions.
Starting from that initial concept, the problem has been assessed through a Multidisciplinary Design Optimization (MDO) approach including dedicated Concurrent Engineering Sessions in the very early phase of the project, where all the partners contributed actively in the project objectives. From an initial trade-off of conceptual designs two preliminary design solutions (one baseline and one backup CES morphing system) emerged as an optimum equilibrium of conflicting objectives among the different disciplines involved, namely: mission analysis, flying qualities, GNC, aerodynamics, aerothermodynamics, structure, mechanisms and system.
Detailed design analyses have been performed on the baseline CES concept to refine the design solution from the perspective of the multiple disciplines involved and to inspect specific features of the flight dynamics, aerodynamics, structures and system. State of the art tools have been used to perform extremely challenging and advanced numerical analyses to characterize the morphing subsystem in the hypersonic morphing phase. From the results obtained and from the challenges faced along the project, multiple areas of interest emerged as potential topics for future investigations.

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2. The SpaceLiner system

An interesting option for hypersonic passenger transport vehicles is a rocket-propelled, suborbital craft. Such a new kind of ‘space tourism’ based on a two stage RLV has been proposed by DLR under the name SpaceLiner [6], [7], [8]. Ultra-long-haul distances like Europe – Australia could be flown in 90 minutes. The functionality of rocket propulsion is a proven technology since decades and their performance characteristics are well known. Furthermore, a rocket powered RLV-concept like the SpaceLiner is highly attractive because the flight durations are two to three times lower than those of even the most advanced airbreathing systems. Although additional times for travel are to be accounted, the actual time needed for travelling with the SpaceLiner on intercontinental routes might still be reduced by 75 % to 80 % compared to conventional subsonic airliner operation.
First proposed in 2005, the SpaceLiner is under constant development and the European Union’s 7th Research Framework Programme has supported several important aspects of its multidisciplinary investigation in multinational cooperation. Another important milestone has been reached in 2016 with the successful completion of the Mission Requirements Review (MRR) which allows the concept to mature from research to structured development.
The last version of the SpaceLiner (version 7-3) and its reference mission are shown in Figure 5. The system is composed of a Reusable Booster (82.3 m in length, 36 m in span, 8.7 m in height with a diameter of 8.6 m) and an Orbiter Stage (65.6 m in length, 33 m in span, 12.1m in height with a diameter of 6.4 m), including the Passenger Cabin (15.6 m in lenght and maximum external height of 5.6 m). The mission is composed of three main phases: a Full Configuration Ascent (from take-off to booster separation, ~75 km, M = 13), an Orbiter Ascent (up to ~68 km, M = 24) and an Orbiter Descent gliding phase.
The Passenger Cabin provides a comfortable pressurized travel compartment (it allows for horizontal entrance of the passengers) and also serves as a reliable rescue system in case of catastrophic events. The cabin is firmly attached to the Orbiter Stage late in the launch preparation process and can be fast and safely separated in flight (through Solid Rocket Motors) in case of an emergency (an event that could occur at any point of the SpaceLiner mission).

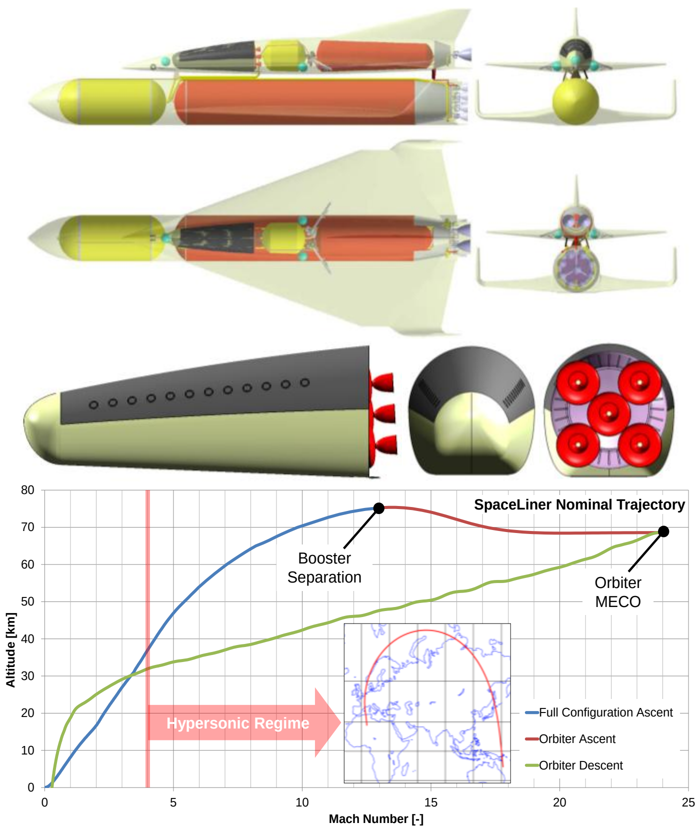

Figure 5: SpaceLiner concept, system design and example of mission profile

The SpaceLiner passenger cabin system and its mission (from hypersonic post-separation conditions to Mach = 3) define the study case and the boundary conditions to the use of morphing in escape systems for hypersonic transport aircrafts investigated in HYPMOCES. Design challenges and benefits of hypersonic morphing solution are explored under the constraints in mass, volume and power imposed by the already-designed SpaceLiner solution: optimum hypersonic morphing design solutions must be compact, lightweight and limited in power but at the same time must enable higher passenger cabin performance (safety first - the capsule should be able to fly safely and autonomously in all separation cases) to compensate the additional complexity introduced. It’s a real multidisciplinary problem.

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3. Concurrent Engineering Session

From a system perspective, the objective is to address the multidisciplinary problem of hypersonic morphing using an integrated engineering approach. The DLR Concurrent Engineering Facility (CEF) is used to support the multi-disciplinary analysis effort for the initial trade-off, bundling the competencies of each partner in an interactive process. Based on the initial SpaceLiner rescue capsule approach provided by the DLR, candidate morphing schemes are proposed prior to, and traded-off during the CE study to identify candidate architectures, which include the use of folding of wings, sliding surfaces, telescopic wings, deformable shape and tilting wings. System requirements for morphing schemes and operational aspects are also formulated beforehand, and evaluated during the CE study. With the contribution of all of the partners, the escape scenario is defined throughout the CEF session and consolidated afterwards. A baseline reference concept and an alternative concept are defined during the CE studies by means of rather quick and approximate analysis tools.
To investigate, define and evaluate the concept of HYPMOCES, a CE study at DLR Bremen was conducted. The study comprised the analysis and the development of all subsystems necessary for the space mission and system, i.e. system engineering, geometry, meshing, aerodynamics, configuration, aerothermodynamics, mission analysis, trajectory, structure, actuators and thermal protection system.
The CE process is based on a concurrent engineering approach and a simultaneous design based on four phases ("IPSP-Approach"): Initiation, Preparation, Study and Post Processing phases, see [9].
The major advantages of the CE process are:

• Very high efficiency regarding time, cost and technical results of a design activity
• Assembly of the whole design team in one room facilitates direct communication and short data transfer times, supported by a moderator
• The team members can easily track the design progress, which also increases personal project identification
• Ideas and issues can be discussed in groups, facilitating for introduction of new viewpoints and solutions, including avoidance and identification of failures and mistakes.

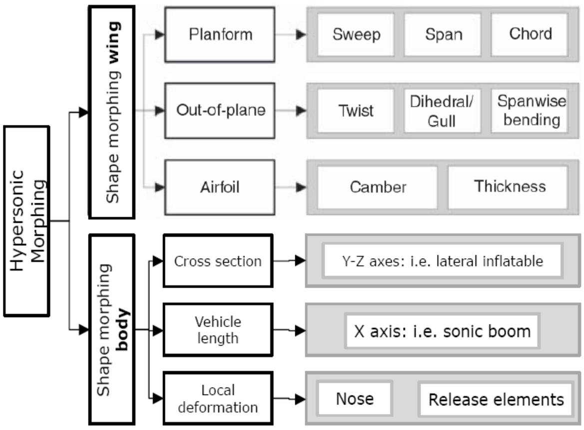

Figure 6: Hypersonic Morphing options

During the **CE Preparation Phase**, a classification of hypersonic morphing features has been derived expanding the surveys performed in the early steps to include morphing of the main vehicle body, see Figure 6. A total of 12 morphing features have been identified as pool of candidates to be combined in the morphing system concepts. Several criteria have been considered to select top features based on non numerical analysis like TRL, cost and complexity; in addition, a list of expected improvement (with respect to the undeployed pre-morphing Cabin Escape System shape) of selected figures of merit based on the team expertise has been considered. Based on this screening, three initial concepts have been identified as most interesting ones during the CE Study Phase

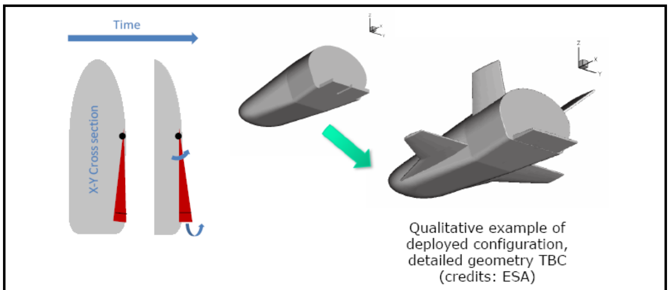

Figure 7: Concept 1

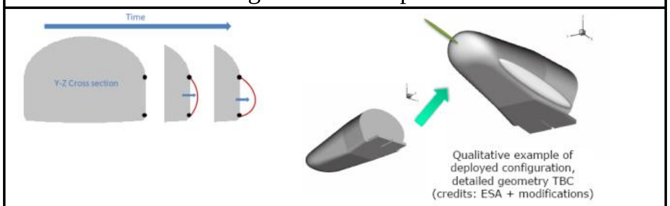

Figure 8: Concept 2

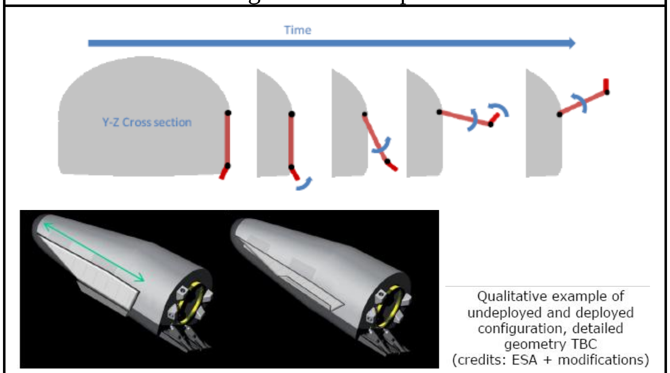

Figure 9: Concept 3

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- **Concept 1** (Figure 7): Sweep + Span + Camber (Wings + Rudders). A wing and two rudders are deployed through pivoting systems that allow a gradual increase of the sweep and span. The wing includes flaps to control the vehicle (it could be an All Moving Surface (AMS))
- **Concept 2** (Figure 8): Cross section + Vehicle length + Camber (Flaps). The main body cross section is modified by means of inflatable systems on the sides of the vehicle. A nose spike is deployed. Body flaps are included to control the vehicle.
- **Concept 3** (Figure 9):Dihedral + Spanwise bending + Camber (Flaps). Two wings are folded on the sides of the main body. Two small winglets are initially deployed and wings are open up by dynamic pressure changing the dihedral up to the final configuration at which wing is locked. Body flaps are included to control the vehicle. Winglet cant and toe angles variations are also proposed.

These three initial concepts have been studied, analysed and refined in the Concurrent Engineering Facility multidisciplinary design session.

4. Multidisciplinary Design Optimisation

The **MDO** problem has been approached by performing an identification of the key disciplines involved (based on partners expertise and tools) and an analysis of the key relationships (interfaces, inputs and outputs) among them.
To visualize this work and to provide the team with a clear and structured framework for the Multidisciplinary Design Analysis (**MDA**, which is the computation core for the calculation of the figures of merits and objectives for the optimisation), a Design Structure Matrix (**DMS**, see Figure 10) has been built.
The DSM shows in a matrix form the following information:

- Diagonal: disciplines and responsible
- Columns: Inputs from other disciplines
- Rows: Outputs for other disciplines

This view enables an easy identification of the interactions between two disciplines: this is highlighted by the off diagonal terms. Three options are possible, depending on the content in the off-diagonal term:

- empty: these two disciplines do not share any input or output: they run in parallel
- filled only in one side of the diagonal: one discipline provides input to the other one: they run in sequence
- filled in both sides of the matrix diagonal: two disciplines share both inputs and outputs meaning that an internal design loop is present there. Convergence is required to a common list of inputs/outputs to guarantee that coherent analyses are performed by both disciplines.

MDO SETTINGS: FIXED	SpaceLiner concept	CES undeployed		SpaceLiner Mission		
MDO SETTINGS: VARIABLE		M shape parameters		Initial abort point Morphing point		
	SYSTEM ENGINEERING & MASSES (DLR)		Vehicle surface, ref. Length. System MCI	Initial state vector (SL7 Trajectory, M>5), Vehicle surface, ref. Length, System MCI	System MCI	System outputs
		GEOMETRY & AERO-THERMODYNAMICS (ONERA)	Undeployed Vehicle Shape, Deployed Vehicle Shape, AEDB Control surface geom.	ATDB Stagnation points radius	Undeployed Vehicle Shape, Deployed Vehicle Shape, Aero-thermo dynamics loads	AETDB outputs
		Control surface deflection	GNC & FQ (DEIMOS)	AEDB (Trim condition)	Desired CoG position	GNC & FQ outputs
		Reynolds, Mach	Reynolds, Mach L/D required	MISSION ANALYSIS & TRAJECTORY (DEIMOS)	Sizing conditions	MA outputs
	Structure mass, power and volume		MCI		TPS, STRUCTURE & ACTUATORS (AVIOSPACE)	Structure & Mech. Outputs
Optimization objectives						FIGURES OF MERIT

Figure 10: Design Structure Matrix, highlighting MDA (green) and MDO interfaces

Common external inputs, fixed or variable, are identified and fed to the MDA function. The variable parameters in particular will be explored within a pre defined range during the MDO process, and are therefore called Design Parameters. The fixed parameters normally are used to define the boundaries of the problem, or design parameters that are constant for a given study case or scenario.
Common external outputs define the performance associated to the MDA. Within the MDO process therefore the effects on the performance given by the variation of the design parameters are explored, in order to quantitatively map their relationship, and identify an optimum solution with respect to the considered scenario
Loops identified in the DSM supported the definition of the main process steps to be followed in the CEF sessions (Figure 11) with the ultimate goal being the computation of the optimisation objectives and of the optimum solutions.

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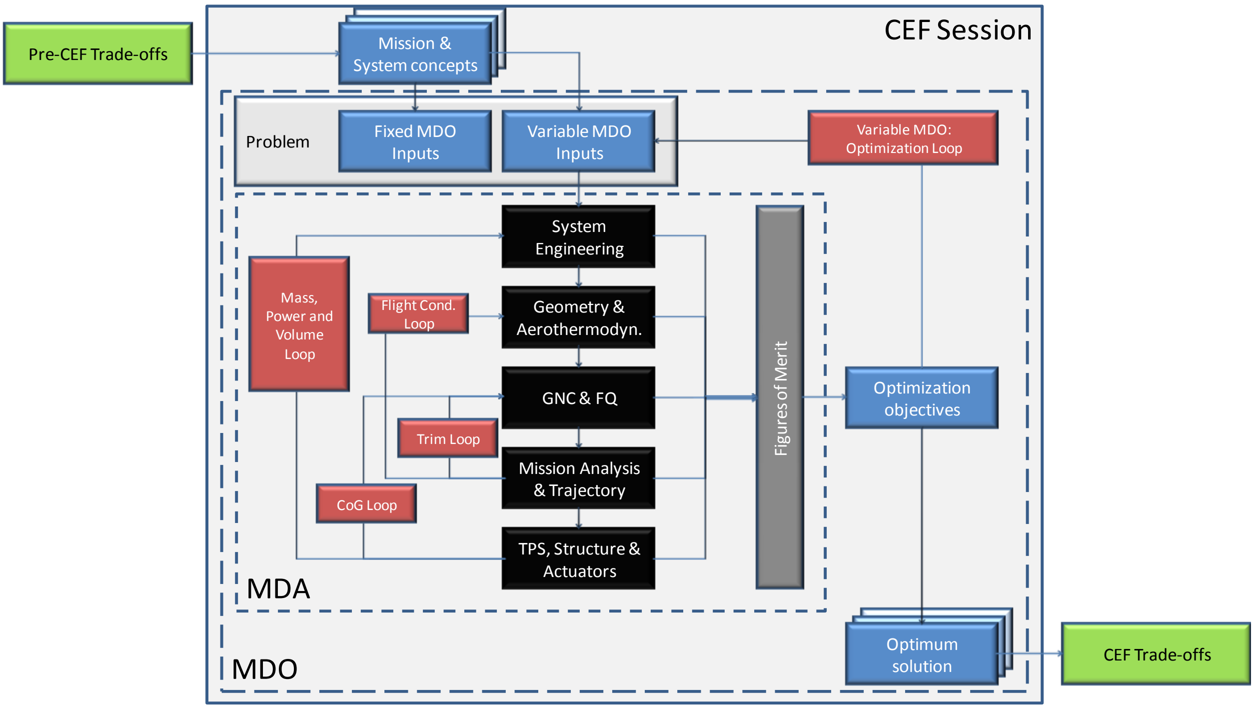

Figure 11: MDO process derived from the DSM and followed during the CEF session

Figure 12: Baseline Concept, CEF design result

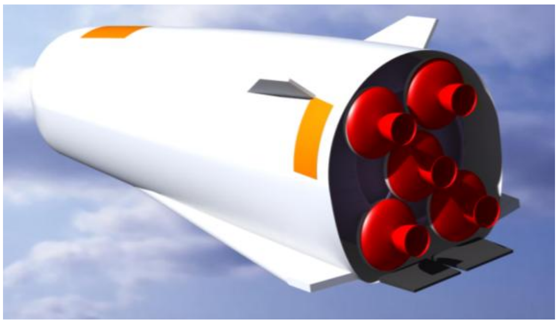

Figure 13: Backup Concept, CEF design result

As a result of the **MDO CE Design Phase**, the following baseline and backup concepts have been designed starting from Concept A and Concept B:

Baseline (Evolution of Concept A, see Figure 12) main features:

This concept relies on the use of an innovative feature for hypersonic morphing: inflatable sidewalls are the key feature implemented in this concept to change the cross section of the vehicle with key benefits:

- improve the overall wet area to increase drag: this is necessary when the vehicle is in an abort condition at high altitude and low speed, to allow a reduction of the vehicle vertical velocity and to achieve a trajectory that is compatible with the entry corridor limits.
- improve the L/D by designing a morphed configuration with a cross profile that helps improving the aerodynamic efficiency
- the introduction of rudders into Concept A has been identified as a necessary evolution to improve lateral-directional flying qualities. Deployable rudders from Concept B have been applied.
- the inflatable sidewalls are designed in the concurrent sessions integrating compromise solutions to conflicting objectives from the point of view of all the disciplines involved.
- flaps have been sized to achieve desired trim capabilities, together with a proper Centre of Gravity (CoG) location selection (coupling flying qualities with system aspects).

Backup (Evolution of Concept B, see Figure 13) main features:

This concept relies on the use of more "classic" features for hypersonic morphing: aerodynamics surfaces are deployed on the vehicle sides to act as wings and rudders are opened up on the top of the vehicle to help the lateral / directional flying qualities performance. These aerodynamic surfaces help into the following aspects:

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- improve the overall wet area to increase drag: this is necessary when the vehicle is in an abort condition at high altitude and low speed, to allow a reduction of the vehicle vertical velocity and to achieve a trajectory that is compatible with the entry corridor limits.
- improve the L/D by designing a morphed configuration with a cross profile that helps improving the aerodynamic efficiency and improve the lateral / directional flying qualities performance

From a system point of view, the Baseline concept is more appealing than the Backup since:

- The overall mass increase is quite reduced: the extra dry mass is just +5% with respect to the undeployed shape while the backup requires an extra dry mass of +18%.
- The inflatable system is quite compact and fits in the available shape with lot of margins. The deployable wing requires a mass, power and volume consuming mechanisms and is by far more complex.
- A solid propellant solution can be easily adopted for the gas generation to inflate the baseline side walls. A distributed mass reduces the change in MCI (Mass, CoG and Inertia) properties when the morphing is performed, helping the GNC with a smooth transition to a different mode.
- The maximum L/D achieved by the baseline is 10% higher than the backup one allowing in a longer range and an easier rescue.

5. Detailed Design

Taking as starting solution the results of the MDO-CEF session, two detailed design loops were performed (lasting 6 and 12 months respectively) to increase the confidence in the results obtained and to analyse the morphing CES in a greater level of details. The analyses were focused on the Baseline concept that was progressively confirmed as the winning one over the set of requirements considered. The main results in the four technical areas covered in the HYPMOCES project are presented in the following subchapters.

5. 1 System design

The activities at system level required the control of the mass, power and volume budgets, guaranteeing coordination of inputs and interfaces among the different disciplines for the proper implementation of design updates in the morphing subsystem and its proper integration in the Cabin System as part of the SpaceLiner Orbiter.

Budgets and CAD files were constantly updated at system level by DLR to introduce detailed modifications in the vehicle internal and external features, in strict collaboration with the structure and mechanisms design team (AVIOSPACE), the aero-thermodynamics team (ONERA) and the Mission Analysis, Flight Mechanics and GNC team (DEIMOS Space). Over the detailed design loops a classic design approach was followed, with the different teams working in parallel on detailed CPU time consuming analysis and with multiple general meetings and check-points to share and discuss intermediate results.

The summary of the mass budget for the Baseline Concept is reported in the table below. The total mass of the morphing system (including also rudders and flaps) is 2455 kg, corresponding to 8.2% of the CES mass (<10% goal). Figure 14 shows the artistic view of the Baseline Concept based on the detailed CAD file generated.

Structure (grey: morphing subsystem)	Body Structure	975.3
	Capsule TPS	3327.3
	Crew Compartment	6552.8
	Inflatable sidewalls	1772.2
	Bags	134.6
	Bags gas	34.2
	Gas Generator	226.8
	Rudders	115.4
	Body flaps	171.8
	Total	13310.3
Subsystems	Total	15676.6
Propulsion	Total	1016.3
CES Total	Total (no margins)	30003.2
	Total + margins	34183.4
	Fuel	3189.8
	Total	**37373.2**

Table 1: Baseline Concept, mass budget

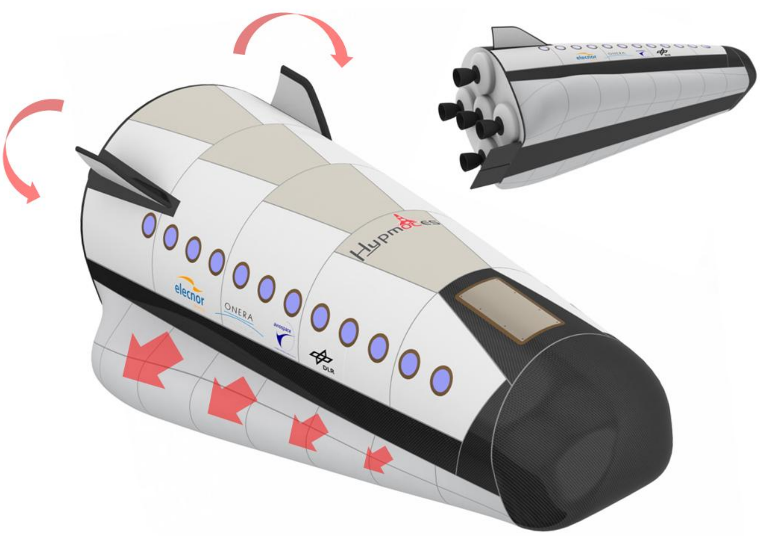
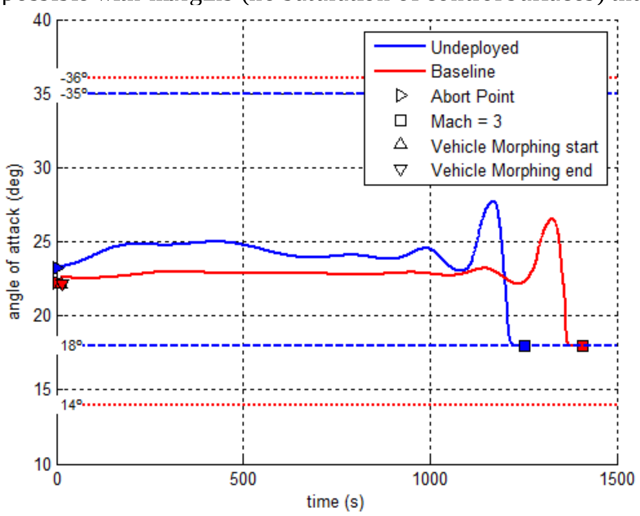


Figure 14: Baseline Concept, detailed design (arrows: morphing)

DOI: 10.13009/EUCASS2017-408

5. 2 Mission Analysis, Flight Mechanics and GNC design

The Mission Analysis (MA) and Flight Mechanics define the flight scenario and they are the source of requirements (ex: sizing trajectories, trim and control surface sizing, vehicle CoG…) for the system and key subsystems like the GNC, the Thermal Protection System and the Structure and Mechanisms. A comprehensive set of mission, flight mechanic and GNC analyses has been performed for the Morphing CES systems under study. Multiple configurations and mission scenarios (covering different abort conditions along the SpaceLiner trajectory) have been analyzed and traded-off supporting the detailed design phase, with special attention to the morphing phase.
For each vehicle configuration considered (Undeployed, Baseline and Backup) a preliminary but extensive aerodynamic databases (**AEDB**) has been computed with HYDRA (a software property of DEIMOS Space [10]) covering a wide range of flight conditions, including Mach, AoA, AoS, elevators deflection and ailerons deflection with a range suitable with the mission needs. As a second step, corrective factors based on high fidelity CFD results from ONERA (see ch.5.3) have been implemented capturing the aerodynamics over key flight conditions. The AEDB generated has been one of the main inputs (together with system inputs and with the Spaceliner mission for the definition of the abort points considered in the project) to the flying qualities and trajectory analyses performed.
More in details, extensive **Flying Qualities** (FQ) analyses have been conducted with the FQA Tool [10] to optimise the vehicle CoG location (through Feasible Domain analysis) and the flight trim line (in the Angle of Attack (AoA) - Mach corridor) as input to trajectory optimisation.
Entry corridors for the cabin escape system have been computed based on a set of thermo-mechanical constraints applied during the hypersonic and supersonic flight; within this entry corridor, **optimised trajectories** have been computed with SGRA [10] from multiple SL7 abort conditions down to Mach = 3, and the optimum morphing point has been identified for each of them (see Figure 15). The optimisation is done with the objectives of improving passengers safety (simplify rescue operations through an extend range flown: +12% achieved by the Baseline concept with respect to the undeployed original CES), improving passengers comfort (reduce thermo-mechanical loads for non-trained personnel: 5% reduction achieved on heat flux and load factor, 13% reduction on dynamic pressure), improve and guarantee appropriate FQ for GNC (trim and lateral stability is achieved). **Sizing** profiles were also derived as specification to the structure and mechanisms design (e.g. heat flux Figure 17).
As a **verification** of the design obtained, extensive FQ Monte Carlo campaign have been run to evaluate the trim, stability and control characteristics of the CES before, during and after the morphing (Figure 16). Morphing is possible with margins (no saturation of control surfaces) thanks to a very careful design of the CoG and trim line.



Parameter	Units	Value: Undeployed	Value: Baseline
Abort Point			
Altitude	km	69.43	69.43
Co-rotating velocity	km/s	7.08	7.08
Mach number	-	23.76	23.76
Morphing Start			
Time since abort point	s	N/A	11.85
Altitude	km		69.30
Co-rotating velocity	km/s		7.07
Angle of attack	deg		22.13
Mach	-		23.69
Morphing End			
Time since abort point	s	N/A	13.85
Mach = 3			
Time since abort point	s	1252.53	1409.70
Altitude	km	22.61	23.50
Downrange from abort point	km	5901.41	6640.69
Crossrange from abort point	km	-586.42	-661.17
LOADS			
Maximum Total Load factor	g	1.44	1.37
Maximum Total Heat Flux	kW/m^2	530.16	500.83
Maximum Total Heat Load	MJ/m^2	456.52	474.84
Maximum dynamic pressure	kPa	23.20	20.23

Figure 15: Example of SGRA trajectory optimisation results (left: trim line – right: summary of performance)

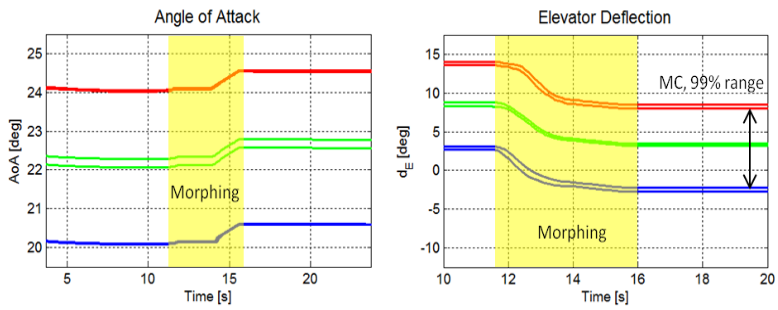


Figure 16: Example of Monte Carlo FQ results (trim during morphing)

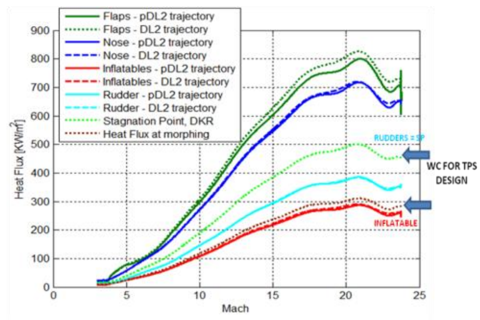


Figure 17: Heat flux sizing profiles

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Strictly coupled with MA, the activities on the GNC subsystem started from the definition of the methodology to generate a general Linear Fractional Transformation / Linear Parameter Varying (**LFT/LPV**) model for a hypersonic vehicle with morphing. Among the several techniques and tools available to Deimos, the exact nonlinear symbolic (reduced-order) LFT generation from symbolically implemented nonlinear models was selected as baseline. Based on the AEDB available, a nonlinear model of the CES has then been derived; the morphing of the vehicle has also been modeled by means of a time-varying parameter upon which the aerodynamic coefficients depend. The LFT/LPV model, of the undeployed cabin escape system has been generated with particular focus to the longitudinal dynamics of the vehicle. LTI point designs were also obtained, based on the nonlinear dynamics, in order to validate the LFT/LPV representation: the stability properties of the vehicle have been analysed, both in the frequency-domain, by using the structured singular value approach, μ, and in the time-domain, by evaluating the time-response of the nonlinear system, when the worst case conditions obtained from the μ approach are used. In particular, the impact of uncertainty of the centre of gravity on the stability of the vehicle has been assessed by using this technique. From a GNC standpoint, one of the main challenges is the system change during the **morphing** phase. In particular, the time-varying nature of morphing has been identified as a key driver in the selection of the control approach.
Several closed loop control methodologies, able to handle time-varying dynamics, have been assessed over different flight conditions, leading to the conclusion that LPV theory was more appropriate than classical control given that it takes advantage of the measured time-varying parameters. Hybrid systems theory has been also identified as a complementary tool to analyse the stability and performance of the vehicle during the transients caused by morphing. Fault Detection and Isolation (**FDI**) techniques have also been implemented and tested, also of a partially morphed vehicle. Hence, the dynamics of the system assuming only one side of the vehicle has undergone morphing were derived.

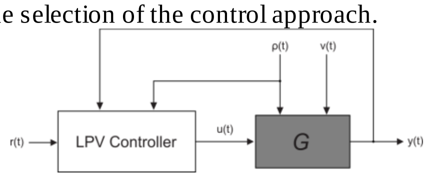

Figure 18: LPV controller scheme

5. 3 Aerodynamics and aero-thermodynamics

Multiple 3D Navier-Stokes computations were conducted on the *undeployed*, *baseline* and *backup* configurations within the frame of the detailed design loop. These high fidelity computations, including “worst case” Mach 20 and Mach 3 conditions, were used to complete and tune the “smooth” AEDB/ATDB databases (see 5.2) developed during the initial phase in order to feed systems and subsystems (MA, FQ, GNC and Structures) detailed analyses with high fidelity aerodynamic and heat loads data. **Parametrical analyses** explored accurately angle of attack effects (+10 to +35°), yawing effects (-5° to -10°), flaps deflections (-10° to +15°), supersonic Mach 3 laminar-to-turbulent transition and non-catalytic wall property effects. Aside of this “smooth” AEDB database, an exhaustive validation of the simplified ONERA design tool FAST was carried out for the detailed loop investigations.
Regarding ATD critical issues occurring during hypersonic re-entry of the escape capsule, additional high fidelity simulations were conducted to address **laminar-to-turbulent transition** at Mach 10, morphing effect of the inflated sidewalls deployment at Mach 20 and updated heating estimate considering a flight configuration of the vehicle at Mach 20. As expected, turbulent status of the boundary layer leads to a second maximum heating point at Mach 10 in the re-entry trajectory, the first one being located at Mach 20 (“worst critical point”).
A fully tubulent calculation was conducted to investigate potential turbulent effects on the heat flux distribution. To be physically representative, a lower altitude was selected, corresponding to a M=10 flight point. The stagnation point heating value obtained including turbulent effects (650 kW/m2) largely exceeds that estimated with a laminar model (200 kw/m2). However, transition to turbulence occurs probably downstream of the nose instead of at the nose itself, and the value at stagnation point delivered by a fully turbulent computation is therefore conservative. Considering the whole capsule, an average ratio of about 2 discriminates laminar heating level to turbulent heating level. For the flaps, the turbulent assumption is more realistic and delivers a flux value around 300 kW/m2.
Moreover, during **morphing** phase discussion, questions raised about **transient effects** on heating sizing policy for inflatable systems of the baseline configuration. Therefore, a transient time-resolved calculation of the initial deployment of the inflatable winged devices (see Figure 19a) was conducted for a 0.4 s second sequence (over the 2s total morphing time which was inaccessible at this time for computing cost): answers were given thanks to this robust calculation that showed that no transient overshoot or undershoot phenomena were present at Mach 20 and steady-state solutions could be then applicable between initial surface and the final inflated one 5 (Figure 19b).
Finally, **micro-aerothermodynamic** simulations of a realistic vehicle (Figure 20) including technological elements like gaps, folding cavities for rudders, stiffeners for flaps, separation thrusters…etc were performed at M=20 thanks to 90 Million mesh cells. These unique computations in the domain of high enthalpy hypersonic sustained optimization investigation for the industrial design of the rescue capsule by providing updated aerodynamic and ATD predictions to partners in charge of GNC, Systems and TPS. Details about the transient and micro-aerothermodynamic simulations can be found in [11].

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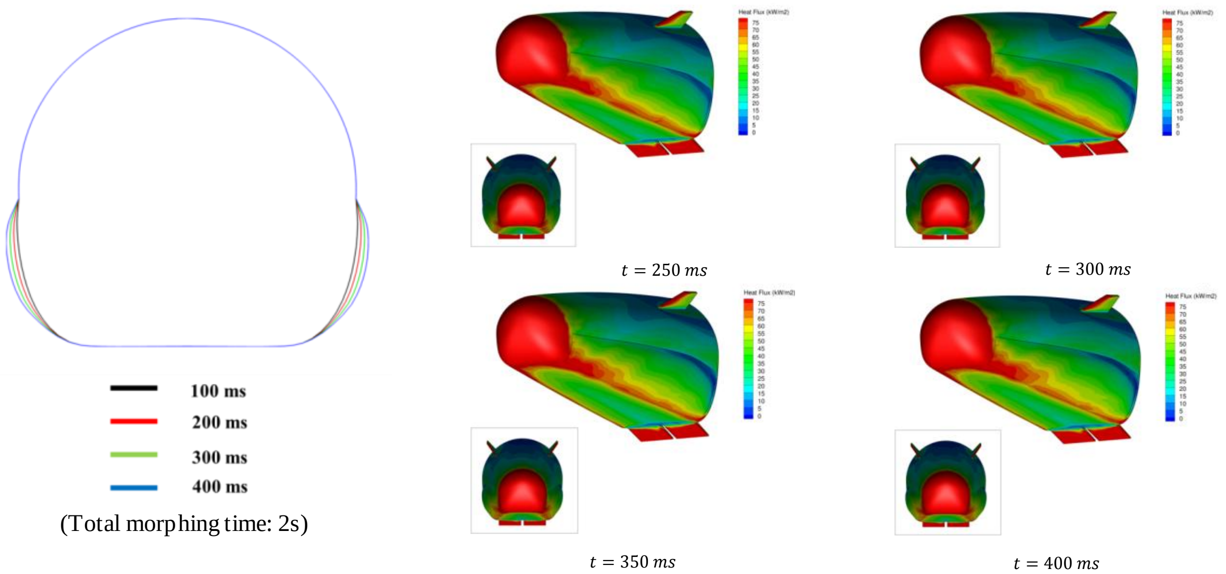

Figure 19 : Morphing geometry (a) Heat Flux time evolution (b) ($200 - 400\ ms$)

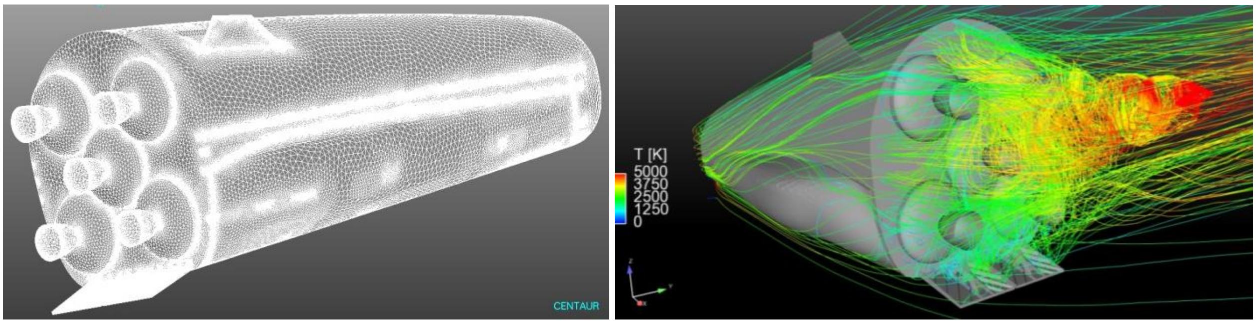

Figure 20 : Surface mesh of the computed vehicle (a) and T along streamlines (b)

5. 4 Structure and mechanisms design

During the detailed design phase, two completely distinct concepts for the morphing system have been developed, basically consisting in a rigid morphing wing (see Figure 13) and an inflatable morphing wing (see Figure 12). The rigid morphing wing is based on a “hot-structure approach” and implies the use of materials withstanding very high temperatures, while the inflatable wing is provided with a gas generator inflating many bags, releasing in turn the flexible thermal protection system (“hot-flexible structure”).

Baseline concept: the inflatable walls are composed by a set of inflatable bags, a gas generator and a thermal-resistant membrane. Following an intensive materials trade-off, the membrane final design is a multi-layers combination of Nextel, Saffil, Pyrogel and Carbon fiber, with gaps strategically located to reduce the overall thermal conductivity. The membrane is composed of two different parts, an upper part that is more flexible (simplifying the deployment phase) and exposed to lower heat fluxes, and a lower part that is thicker and stiffer to sustain higher thermo-mechanical loads.

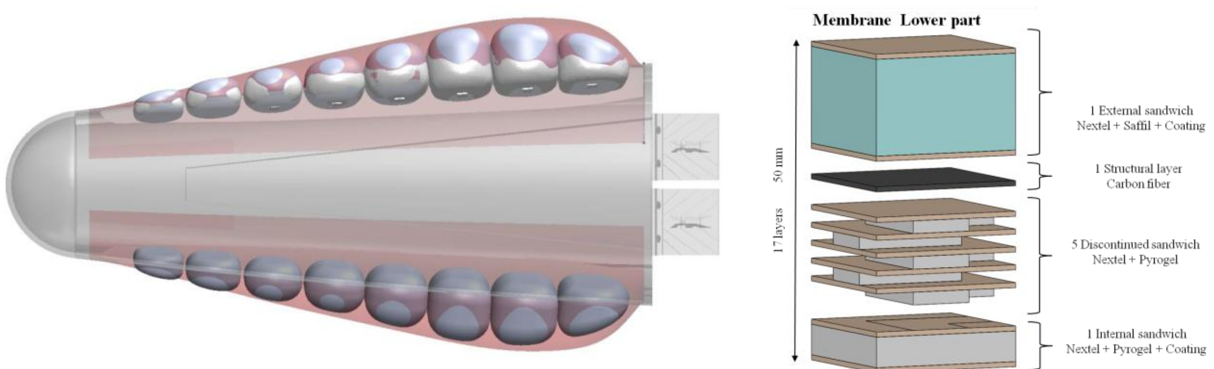

Figure 21: Baseline Concept, mechanical and structural design

DOI: 10.13009/EUCASS2017-408

Bags are composed of Kapton, Kevlar and Zylon fabric in a multi-layer configuration with multiple Dyneema and Zylon belts joined to the supporting structure to aid the inflated shape in keeping the desired position. The deployment process has been modelled, optimised and finally tested through state-of-the-art LS-Dyna thermo-structural simulations. This tool allows a full dynamic explicit simulation including multiple non linear effects at the price of very high CPU time. The results obtained (simulation based on 690'000 deformable elements, 1'350'000 rigid elements, Physical time: 3 s, Time step ≈3e-6 s, CPU time @ 4 core: ≈ 1 month) indicate that the overall concept is technically feasible but still additional work is necessary to tune and optimise specific design details to avoid observed contact and stability issues. Material characterization through specimen testing is also recommended.

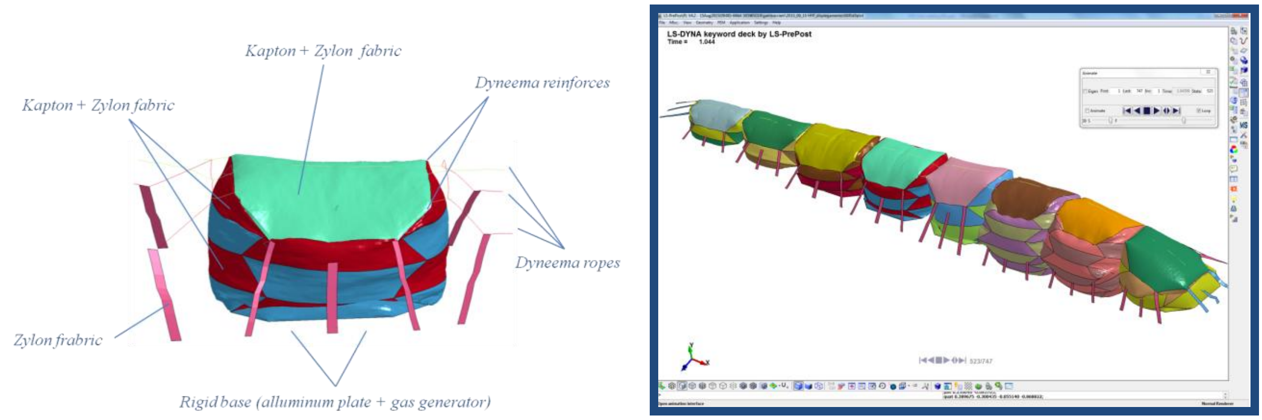

Figure 22: Baseline Concept, design solution and LS-Dyna thermo-structural simulation of bags inflation

Backup concept: in the stowed configuration, the wing is completely inside the vehicle and fills the little free volume between the pressure vessel and the external TPS. Ejectable TPS tiles fill the gap to the wing leading edge.
The design of the wing, in the deployed configuration, is affected by constraints on the aerodynamic shape due to the need to guarantee an optimal interface with the original TPS, limiting critical thermal aspects. The wing presents a perfect flat and smooth surface with cross-sections characterized by decreasing thickness from the root to the tip, avoiding open cavities that would lead to an inflow of extremely high-temperature gas into the vehicle, affecting dramatically its operations during flight. The sealing between the capsule and the deployed wing is furthermore ensured by the overlap of the wing remaining in part internal to the capsule and the TPS. The leading edge presents a continuous and smooth surface over the whole length for mechanical and thermal constraints. Sharp edges or very small radii induce in fact strong local temperature increases and stress accumulations to be avoided, hence, a well-rounded leading edge's curvature is assumed over the wing's thickness. The wing is made of a Titanium and Inconel core, covered by Pyrogel and C/SiC panels (on the wing edges). The wing deployment is based on a hinge mechanism aided by preloaded springs fixed to both wing roots at regular intervals.

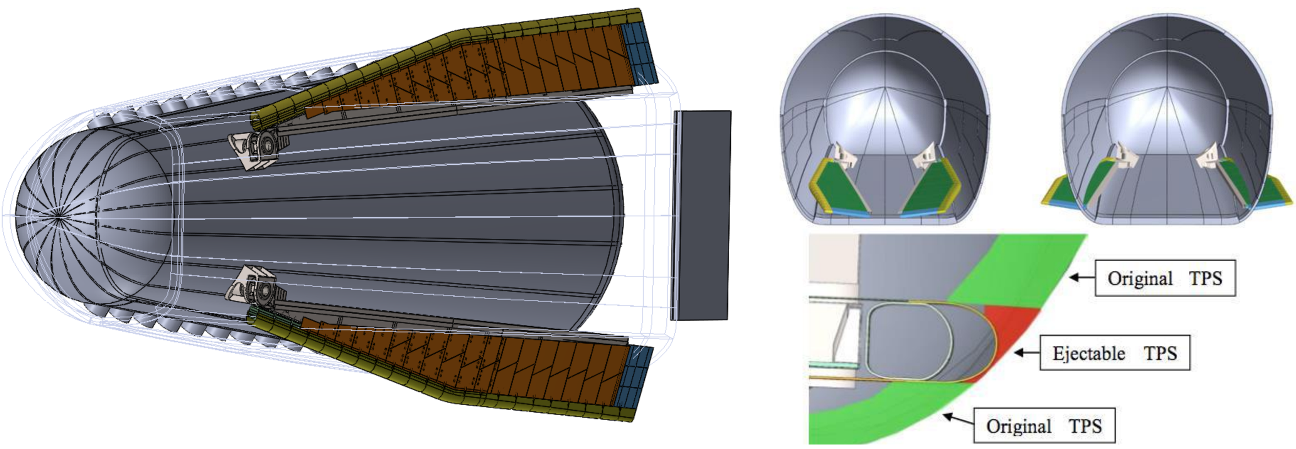

Figure 23: Backup Concept, mechanical and structural design

Common elements: deployable rudders and moving flaps are also part of the morphing features of the Cabin Escape System design for both the Baseline and the Backup configurations. The structures and mechanisms have been designed for both, resulting in more classic solutions for hypersonic flight (monolithic C/C-SiC main body solution, spring and lock mechanism for rudder and electro-mechanical actuators for flaps).

DOI: 10.13009/EUCASS2017-408

6. Conclusions

The HYPMOCES project allowed the investigation and development of technologies in the area of control, structures, aerothermodynamics, mission and system required to enable the use of morphing in escape systems for future hypersonic transport aircrafts. Multiple challenges have been faced in the complex multidisciplinary problem addressed : a morphing hypersonic cabin escape system. Strict coupling and tight interactions among the key disciplines considered in this work required a concurrent design approach since the very beginning of the project. Mutlidisciplinary Design Optimization (MDO) techniques have been adopted to identify an initial set of interesting candidate solutions. A baseline design concept emerged as the winning one, based on innovative inflatable sidewalls and deployable rudders. In a second step, the MDO solutions have been further refined by detailed design analyses and extensive numerical simulations that have been pushed to the limit the complexity that can be currently handled by state of the art tools (especially in the areas of Flying Qualities and GNC reconfiguration, aerodynamics and structures). The coordination at system level played a key role to set the boundaries to the design and to harmonize changes to a system already designed for a challenging mission: the cabin system of a hypersonic passenger transport vehicle. Multiple areas of interest emerged as potential topics for future investigations, for example: system failure management at GNC level, aerothermodynamic analyses of deformable hypersonic vehicles, structures and fluid interactions of innovative materials for inflatable concepts in hypersonics, flexible TPS material characterization through specimen testing. Morphing concepts explored here could find applications to unmanned vehicles in supersonic or subsonic flight regimes and have commonalities with recent game-changing solutions under study for future planetary probe exploration (e.g. [2]).

7. Acknowledgments

The research leading to these results has received funding from the European Union’s Seventh Framework Program FP7/2007-2013 under grant agreement n° ATT-2012-RTD-341531 entitled “Hypersonic Morphing for a Cabin Escape System (HYPMOCES)”.
The authors would like to thank the full HYPMOCES project team for the outstanding work performed.

References

[1] Barberino et al. 2001. A Review of Morphing Aircraft. JOURNAL OF INTELLIGENT MATERIAL SYSTEMS AND STRUCTURES, Vol. 22—June 2011.
[2] Dr. Neil Cheatwood. Hypersonic Inflatable Aerodynamic Decelerator (HIAD) Technology. NASA’s Game Changing Technology, Industry Day, June 29-30, 2016
[3] Dr. Peter Gage and P. Werchinski. Hypersonic Deployable Decelerators Adaptable, Deployable Entry Technology and Placement (ADEPT) Project. IPPW-10, June 15, 2013.
[4] R.D. Braun, R.Manning. Mars exploration entry, descent and landing challenges. Aerospace Conference, 2006 IEEE, 4-11 March 2006
[5] ZEHST. High-Speed Transport Concept Study. EADS brochure.
[6] Sippel, M., Trivailo, O., Bussler, L., Lipp, S., Kaltenhäuser, S.; Molina, R.: Evolution of the SpaceLiner towards a Reusable TSTO-Launcher, IAC-16-D2.4.03, September 2016
[7] Sippel, M.; Bussler, L.; Kopp, A.; Krummen, S.; Valluchi, C.; Wilken, J.; Prévereaud, Y.; Vérant, J.-L.; Laroche, E.; Sourgen, E.; Bonetti, D.: Advanced Simulations of Reusable Hypersonic Rocket-Powered Stages, AIAA 2017-2170, 21st AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 6-9 March 2017, Xiamen, China
[8] Sippel, M.; Valluchi, C.; Bussler, L.; Kopp, A.; Garbers, N.; Stappert, S.; Krummen, S.; Wilken, J.: SpaceLiner Concept as Catalyst for Advanced Hypersonic Vehicles Research, 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan, 2017
[9] T. Schwanekamp et al. Concurrent Engineering Approach for the Preliminary Study of Hypersonic Morphing for a Cabin Escape System, 65th IAC, IAC-14.D1.3.10. Toronto, Canada, 2014.
[10] D. Bonetti, C. Parigini, G. De Zaiacomo, I. Pontijas Fuentes, G. Blanco Arnao, D. Riley, M. Sánchez Nogales, PETBOX: FLIGHT QUALIFIED TOOLS FOR ATMOSPHERIC FLIGHT. 6th International Conference on Astrodynamics Tools and Techniques (ICATT), Darmstadt, 2016.
[11] E. Laroche, Y.Prévereaud, J.-L.Vérant, M.Sippel, D.Bonetti, Micro-Aerothermodynamics Analysis of the SpaceLiner Cabin Escape System along Atmospheric Re-entry. 7th European Conference for Aeronautics and Space Sciences (EUCASS), Milan, 2017