Ultra-Fast Passenger Transport Options Enabled by Reusable Launch Vehicles

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ABSTRACT

The latest architecture of the SpaceLiner 7 configuration is described including major geometrical and mass data. Some elements of the next iteration step, the SpaceLiner 8, are highlighted, having its focus on most recent analyses, partially not previously published

A passenger rescue capsule is intended to be used in case of extreme emergencies. The design of the cabin and the ejection system is refined in a systems engineering approach to obtain a feasible and viable solution. Multibody simulations of the emergency capsule separation are performed in a wide range of flight conditions and technical challenges are identified.

The adaptation of the large unmanned booster stage, currently under way might include a new wing lay-out capable of swiveling-out in the lower speed regime. Advantages and technical challenges of this approach are addressed in the paper.

Simulated 6DOF ascent trajectories analyze behavior of the Thrust Vector Control system in case of wind and gusts interacting with the winged configuration in nominal and off-nominal conditions.

Keywords: RLV, SpaceLiner, TSTO, rocket-propulsion, rescue capsule

Nomenclature

D	Drag	N
I_{sp}	(mass) specific Impulse	s (N s / kg)
L	Lift	N
M	Mach-number	-
T	Thrust	N
W	weight	N
g	gravity acceleration	m/s^2
m	mass	kg
q	dynamic pressure	Pa
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-

Subscripts, Abbreviations

AOA	Angle of Attack
BFR	Big Falcon Rocket
BFS	BFR ship
CAD	Computer Aided Design
DOF	Degree of Freedom
GLOW	Gross Lift-Off Mass
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
MR	Mixture Ratio
MRR	Mission Requirements Review
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
SI	Structural Index
SLC	SpaceLiner Cabin
SLME	SpaceLiner Main Engine
TPS	Thermal Protection System
TRL	Technology Readiness Level
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control
CoG	center of gravity
cop	center of pressure

1 INTRODUCTION

Recently, the launcher development has become highly dynamic again. Major technical successes are achieved in rapid succession wit key players the US companies SpaceX and Blue Origin. Falcon 9 is now routinely returning the used first stages with high accuracy back to Earth.

However, the end of development is not yet reached and even more ambitious plans were announced in 2017, the development of a very large, fully reusable two-stage launcher to LEO, called “BFR” [1]. This vehicle now renamed Starship and Super Heavy is planned as an interplanetary manned space-ship and as an ultrafast rocket-based point-to-point transport on Earth.

Multiple mission reusable launch vehicles could be an interesting and attractive option for the future with cost saving potential. A similar RLV-configuration capable of fulfilling very different needs might significantly reduce the development effort compared to the individual developments of several dedicated crafts. Further, the production reaching higher numbers for the same type will likely have a positive impact on manufacturing expenses.

DLR’s SpaceLiner concept is similar in certain aspects to the idea of multiple-mission reusable launch vehicles. These concepts are understood to serve quite diverse missions by the same or at least a similar vehicle. [2]. While its primary role is conceived as an ultrafast intercontinental passenger transport, its secondary role is intended as an RLV capable of delivering heavy payloads into orbit.

This paper does not intend on providing a complete technical overview of the SpaceLiner, but instead focusing on most recent analyses, partially not previously published. After describing the latest SpaceLiner 7’s consolidated technical status, some of the most critical points of the ongoing development progress are addressed: This includes multi-body simulations of the rescue capsule separation procedure, a new potential lay-out of the SpaceLiner 8 booster configuration, followed by the controllability assessment of the ascent flight of the winged configuration in nominal and off-nominal conditions.

2 SPACELINER 7 ARCHITECTURE AND GEOMETRY

First proposed in 2005 [3], the SpaceLiner is under constant development and descriptions of some major updates have been published since then [4, 6, 9, 12, 13]. The European Union’s 7th Research Framework Programme has supported several important aspects of multidisciplinary and multinational cooperation in the projects FAST20XX, CHATT, HIKARI, and HYPMOCES. In the EU’s Horizon 2020 program the new project FALCon addresses an advanced return mode of the reusable booster stage [7].

At the end of 2012 with conclusion of FAST20XX the SpaceLiner 7 reached a consolidated technical status. An important milestone has been achieved in 2016 with the successful completion of the Mission Requirements Review (MRR) which allows the concept to mature from research to structured development [12, 14]. The Mission Requirements Document (MRD) is the baseline and starting point for all technical and programmatic follow-on activities of the SpaceLiner Program.

The parallel arrangement of the two reusable vehicles at lift-off is presented in Figure 1: a large unmanned booster stage and a passenger or orbital upper stage. All 11 SLME engines are operating right from lift-off, 9 on the booster and 2 on the upper stage which is fed by propellant crossfeed in the mated section of the flight. External shapes of passenger and orbital configuration with satellite payload are almost identical. This approach intends enabling dramatic savings on development cost and moreover by manufacturing the vehicles on the same production line, also significantly lower hardware cost than would result for a dedicated new lay-out [12].

The internal arrangement of the upper stage is adapted to the specific mission with either a forward passenger cabin or a central cargo bay and adequately placed LOX-tank (Figure 1). The main dimensions of the 7-3 booster configuration are listed in Table 1 while major geometry data of the SpaceLiner 7-3 passenger or orbiter stage are summarized in Table 2.

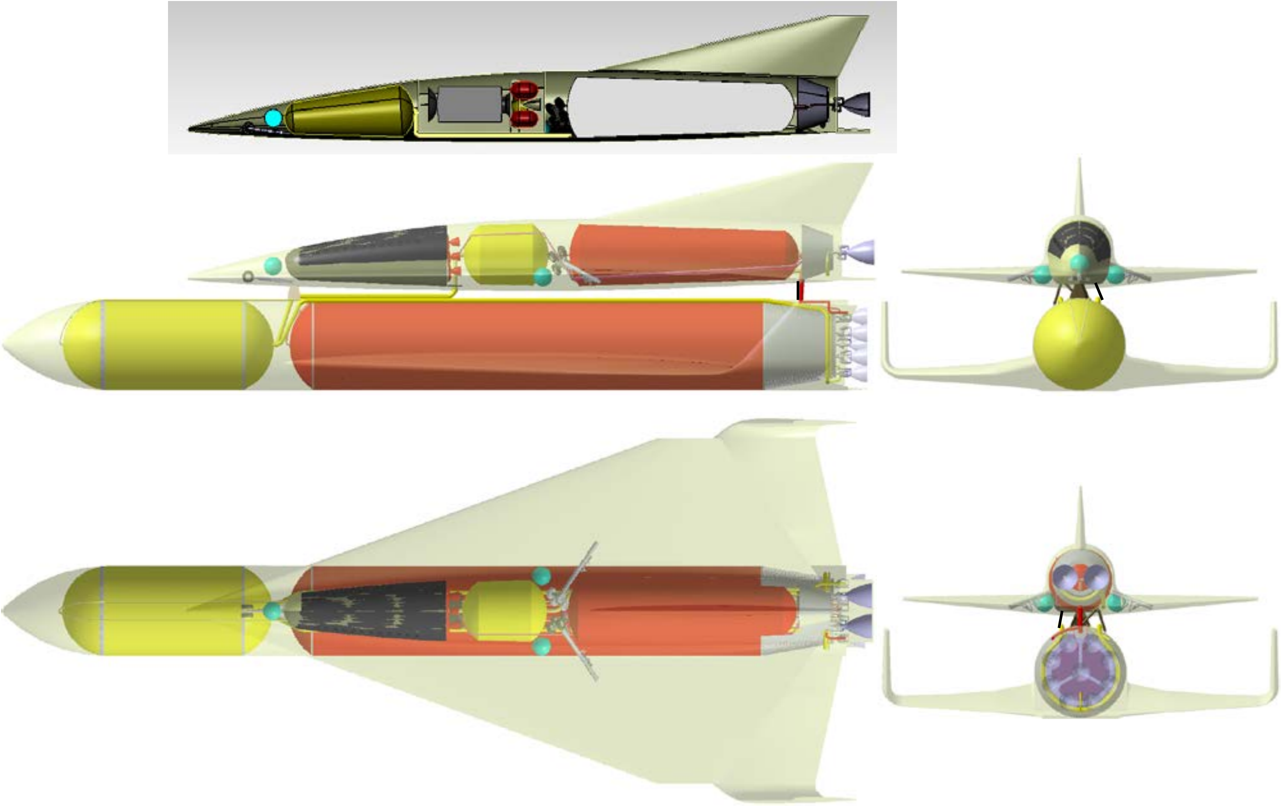

Figure 1: Sketch of SpaceLiner 7 launch configuration with passenger stage (SLP) with its booster stage at bottom position and orbital stage of SLO in insert at top

Table 1: Geometrical data of SpaceLiner 7-3 booster stage

length [m]	span [m]	height [m]	fuselage diameter [m]	wing leading edge angles [deg]	wing pitch angle [deg]	wing dihedral angle [deg]
82.3	36.0	8.7	8.6	82/61/43	3.5	0

Table 2: Geometrical data of SpaceLiner 7 orbiter and passenger stage

length [m]	span [m]	height [m]	max. fuselage diameter [m]	wing leading edge angle [deg]	wing pitch angle [deg]	wing dihedral angle [deg]
65.6	33.0	12.1	6.4	70	0.4	2.65

2.1 Reusable booster stage

The SpaceLiner 7 booster geometry is relatively conventional with two large integral tanks with separate bulkheads for LOX and LH2 which resembles the Space Shuttle External tank layout. The major additions to the ET are an ogive nose for aerodynamic reasons and for housing subsystems, the propulsion system, and the wing structure with landing gear.

The overall size of the booster is reaching significant dimensions of more than 80 m in length. The current configuration of the booster has been defined based on extensive analyses of the propellant crossfeed system [8], pre-design of major structural parts like tanks, intertank and the thrust frame. The structure of the wing follows aircraft convention with ribs to make up the shape of the wing profile and spars to carry the main bending load [13]. Both tanks with an external structural diameter of 8.5 m carry all major loads. Major geometrical data of this configuration 7-3 are listed in Table 1.

2.2 Reusable upper stage

The SpaceLiner7 aerodynamic shape is a result of a trade-off between the optima of three reference trajectory points and shows considerable improvements in glide ratio and heat loads compared with previous designs and points out the clear advantages of a single delta wing [9]. Major geometry data of the SpaceLiner 7-3 passenger and orbiter stage are summarized in Table 2. The SpaceLiner passenger stage's shape with the cabin located in the nose section (note illuminated windows) is shown in Figure 2.

Figure 2: The SpaceLiner 7-3 rocket-propelled intercontinental passenger transport in final horizontal landing approach

The passenger stage needs to be redesigned for its secondary role as an unmanned satellite launcher. The passenger cabin (see section 3 below!) is not needed in this configuration and is to be replaced by a large internal payload bay.

Key geometrical constraints and requirements are set such that the SpaceLiner 7 passenger stage's outer mold line and aerodynamic configuration including all flaps should be kept unchanged. The internal arrangement of the vehicle could be adapted; however, maximum commonality of internal components (e.g. structure, tanks, gear position, propulsion and feed system) to the passenger version is preferred because of cost reflections. Further, the payload bay should provide sufficient volume for the accommodation of a large satellite and its orbital transfer stage.

The stage's propellant loading has been reduced by 24 Mg to 190 Mg with a smaller LOX-tank to allow for a payload bay length of 12.1 m and at least 4.75 m diameter. These dimensions are close to the Space Shuttle (18.3 m x 5.18 m x 3.96 m) and should accommodate even super-heavy GTO satellites of more than 8 m in length and their respective storable upper stage (Figure 3). Large doors open on the upper side to enable easy and fast release of the satellite payload in orbit.

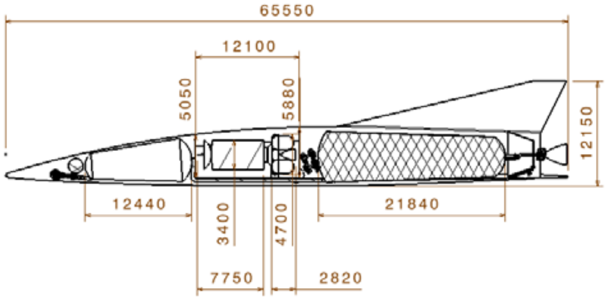

Figure 3: Sketch of SpaceLiner 7 as orbital space transportation with internal cargo bay for satellites

The aerodynamic trimming with the existing trailing edge flaps and the bodyflap has been preliminarily checked in numerical simulations under hypersonic flow conditions and is found feasible within the constraints of the present lay-out. This promising outcome is a result of the robust SpaceLiner design philosophy, which is also taking into account off-nominal abort flights. The calculated maximum L/D is reduced approximately 15% by the significant flap deflections compared to the L/D achievable for the nominal passenger mission with almost no deflection.

2.3 Main propulsion system

Staged combustion cycle rocket engines with a moderate 16 MPa chamber pressure have been selected as the baseline propulsion system right at the beginning of the project [4]. A Full-Flow Staged Combustion Cycle with a fuel-rich preburner gas turbine driving the LH2-pump and an oxidizer-rich preburner gas turbine driving the LOX-pump is the preferred design solution for the SpaceLiner [8]. The expansion ratios of the booster and passenger stage/ orbiter engines are adapted to their respective optimums; while the mass flow, turbo-machinery, and combustion chamber are assumed to remain identical in the baseline configuration.

The SpaceLiner 7 has the requirement of vacuum thrust up to 2350 kN and sea-level thrust of 2100 kN for the booster engine and 2400 kN, 2000 kN respectively for the passenger stage. All these values are given at a mixture ratio of 6.5 with a nominal operational MR-range requirement from 6.5 to 5.5. Table 3 gives an overview about major SLME engine operation data for the nominal MR-range as obtained by cycle analyses.

The size of the SLME in the smaller booster configuration is a maximum diameter of 1800 mm and overall length of 2981 mm. The larger passenger stage SLME has a maximum diameter of 2370 mm and overall length of 3893 mm. A size comparison of the two variants and overall arrangement of the engine components is published in [8]. All engines have a 2D TVC capability electro-mechanically actuated.

The engine masses are estimated at 3375 kg with the large nozzle for the passenger stage and at 3096 kg for the booster stage. These values are equivalent to vacuum T/W at MR=6.0 of 68.5 and 72.6 [8].

2.4 Launcher system stage masses

Based on available subsystem sizing and empirical mass estimation relationships, the passenger stage mass is derived as listed in Table 5. The total fluid and propellant mass includes all ascent, residual, and RCS propellants and the water needed for the active leading edge cooling [4, 11, 12]. The stages' MECO mass is approximately 151.1 Mg. The SpaceLiner 7-3's GLOW reaches about 1832 Mg (Table 7) for the reference mission Australia – Europe while the TSTO is at 1807 Mg (Table 8) still below that of the Space Shuttle STS of more than 2000 Mg.

The structural index of the SpaceLiner booster stage is 15.6%. The orbiter stage reaches almost 50% and the passenger stage with its capsule even 55% SI. The relatively high structural indices of the SpaceLiner are linked to the intentionally robust design philosophy of the concept.

Table 3: SpaceLiner Main Engine (SLME) technical data [8]

	Booster			Passenger Stage		
Mixture ratio [-]	5.5	6.0	6.5	5.5	6.0	6.5
Chamber pressure [MPa]	15.1	16.0	16.9	15.1	16.0	16.9
Mass flow per engine [kg/s]	481	517	555	481	518	555
Expansion ratio [-]	33	33	33	59	59	59
Specific impulse in vacuum [s]	439	437	435	451	449	448
Specific impulse at sea level [s]	387	389	390	357	363	367
Thrust in vacuum per engine [kN]	2061	2206	2356	2116	2268	2425
Thrust at sea level per engine [kN]	1817	1961	2111	1678	1830	1986

Table 4: Mass data of SpaceLiner 7-3 booster stage

Structure [Mg]	Propulsion [Mg]	Subsystem [Mg]	TPS [Mg]	Total dry [Mg]	Total propellant loading [Mg]	GLOW [Mg]
123.5	36.9	18.9	19.1	198.4	1272	1467

Table 5: Mass data of SpaceLiner 7-3 passenger stage

Structure [Mg]	Propulsion [Mg]	Subsystems including cabin [Mg]	TPS [Mg]	Total dry [Mg]	Total fluid & propellant loading [Mg]	GLOW incl. passengers & payload [Mg]
55.3	9.7	43.5	22.3	129	232.1	366

Table 6: Mass data of SpaceLiner 7 Orbiter stage (GTO mission)

Structure [Mg]	Propulsion [Mg]	Subsystems [Mg]	TPS [Mg]	Total dry [Mg]	Total fluid & propellant loading [Mg]	GLOW incl. kick-stage & payload [Mg]
60.1	9.9	9.8	22.3	102	207	309.1

Table 7: Mass data of SpaceLiner 7-3 passenger launch configuration

Total dry [Mg]	Total propellant loading [Mg]	GLOW incl. passengers & payload [Mg]
327.4	1502	1832.2

Table 8: Mass data of SpaceLiner 7-3 TSTO launch configuration

Total dry [Mg]	Total propellant loading [Mg]	GLOW incl. kick-stage & payload [Mg]
300.6	1467	1807

3 CABIN AND RESCUE SYSTEM

The passenger cabin of the SpaceLiner has a double role. First providing a comfortable pressurized travel compartment which allows for horizontal entrance of the passengers, and second serving as a reliable rescue system in case of catastrophic events. Thus, the primary requirements of the cabin are the possibility of being firmly attached late in the launch preparation process and fast and safely separated in case of an emergency.

The capsule should fly autonomously back to Earth's surface in all separation cases. The abort trajectories are primarily influenced by the mass of the capsule and the aerodynamic performance with the most important subsystems being the separation motors, the thermal protection system (TPS), and the structure. These three subsystems have been investigated and sized for function, performance, and mass [10, 12, 13].

Overall length of the capsule without separation motors is 15.6 m and its maximum external height is 5.6 m. The estimated masses are about 26.4 tons for the dry capsule (reference SpaceLiner 7-3), about 7600 kg for the passengers, crew and luggage, and 3400 kg for all propellants of separation motor, retro-rockets and RCS [13].

A fundamental requirement for the design of the rescue capsule is its integration in the front section of the passenger stage. The capsule should be separated as easily and quickly as possible. Therefore, it cannot be an integral part of the fuselage structure, however, its upper aft section is conformal with the SpaceLiner's fuselage while the lower side is fully protected by the fuselage bottom structure (Figure 1). Alternative capsule integration concepts have been proposed and technically analyzed [10]. However, each of the explored design options is linked to severe challenges and drawbacks. Systematic investigations are ongoing to find a promising and reliable system. Some results from the corresponding multibody simulations are described in the following section.

3.1 SLC separation studies

The current requirement of capsule separation being feasible at any flight condition and attitude is highly challenging from a technical point of view. Analyses revealed some critical issues to be addressed in order to improve the safe functionality of the cabin rescue system.

Multibody 6DOF-simulations using Simpack have been set up for the analyses of the baseline SLC integration concept because a consolidated design with extensive data sets is available [10]. The geometrical model was taken from the respective SpaceLiner CATIA model and is shown in its Simpack simplification in Figure 4. The investigation logic requires at first, understanding the implications of the separation maneuver under all relevant conditions. 6DOF-multi-body dynamics with inertia matrices are taken into account with the aerodynamic coefficients still simplified. The latter is due to the lack of data and accepted for the first step. The SLC attitude data like AoA and flight Mach-number from these simulations are subsequently to be used for performing dedicated CFD-calculations delivering enhanced coefficients and which should study critical flow-interaction effects. Based on this first round of numerical studies, an improved understanding of system requirements can be derived which should allow to study alternative, potentially better design and integration options.

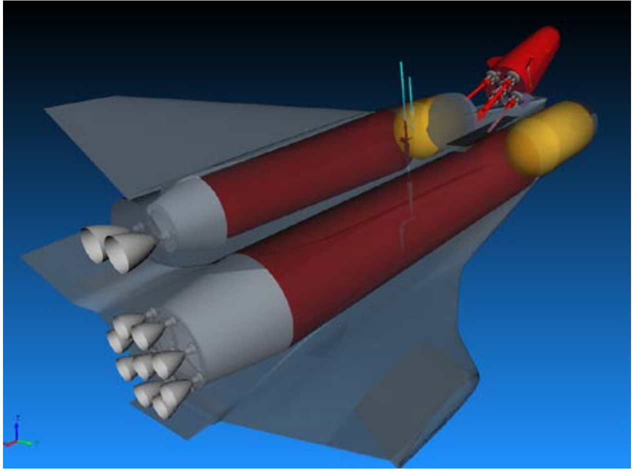

Figure 4: SLC separation simulation in Simpack model with separated capsule and thrust vectors shown in red

In the first step, five abort cases with SLC ejection along the nominal operational flight have been studied: at the launch pad prior to lift-off with zero altitude and zero velocity of the SpaceLiner, at maximum dynamic pressure in transonic flow conditions, at SLB separation, at SLP MECO all during the ascent and one in gliding hypersonic flight close to maximum heatflux. The emergency on the launch pad is a design driver of the separation motors because of the requirement to rapidly escape the huge detonation potential of the propellant loading in the completely filled tanks and further to reach sufficient altitude for subsequent parachute landing in a safe distance.

A typical result from the huge data sets generated is shown in Figure 5 presenting the axial accelerations acting on a seat in the most forward position of the SLC depending on the separation conditions. After the nose tilt-up of about 0.2 s, the outboard separation motors are ignited within 0.1 seconds after ignition of the center motor. The solid rockets burn for about 2 seconds and produce a maximum thrust of slightly more than 850 kN each. Around 0.4 s after initiation of the process approximately 12 g are reached with burn duration of 2 s. Medical investigations of NASA had demonstrated in the past that even untrained passengers will endure such elevated acceleration levels for such a short time if pushed back into their seats. After burn-out the acceleration level is rapidly decreasing and aerodynamic drag is acting as a decelerator. Note that four of the simulated cases show overall similar behavior. A remarkable difference is visible for separation at maximum dynamic pressure. The strong aerodynamic drag is influencing the acceleration profile and some oscillation is visible which is due to relatively fast rotation of the capsule.

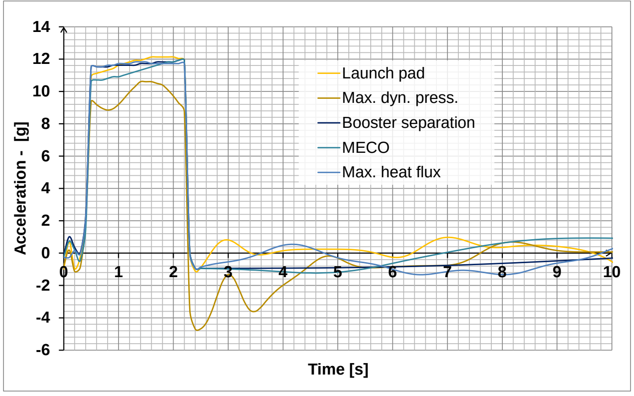

Figure 5: Axial acceleration acting on fwd. seat in SLC separation procedure obtained for different cases of Simpack simulations

Several data sets in addition to the one shown in Figure 5 are under evaluation. Preliminary results clearly indicate that SLC separation at maximum dynamic pressure in transonics during ascent flight is highly critical and might not be feasible. Further assessment should find a relatively short period of time during which the separation sequence should be blocked for safety reasons.

4 BOOSTER REDESIGN INVESTIGATIONS TO PREPARE FOR SLB8

The biplane architecture of the mated launch configuration (Figure 1) is problematic because of complex high-speed flow interactions of the two stages during ascent flight. Even more critical is a shock-shock interaction at the outboard leading edge during atmospheric reentry and maximum aerothermal loads [13]. Currently, the study for the next SpaceLiner 8 design targeting major improvements is ongoing without yet any downselection performed. However, some early results of the research are already presented in the following sections.

4.1 SLB8-V2

In order to reduce biplane flow interactions during ascent and to avoid the shock-shock-interaction on the outboard leading edge, a drastically reduced size of the SLB wing has been investigated as a first proposal for the Booster, called SLB8V2. Such a small wing will not be sufficient for horizontal landing of the RLV-stage with its more than 180 Mg of dry mass. L/D is also not satisfactory to allow the tow-back using the “in-air-capturing”-technique. Consequently, the SLB8V2 would need to be designed for vertical downrange landing on a sea-going ship.

However, the vertical landing SLB8V2 was found to be not promising because of severe controllability issues with the required pitch-over maneuver and also not being attractive from a weight perspective [13]. Alternative design options have been explored which are described in the following section.

4.2 SLB8-V3

The promising hypersonic aerodynamic configuration of the SLB8V2 with its relatively small wings is maintained. In order to allow, as for previous variants, the stage to use "in-air-capturing" [7] and horizontal landing, deployable wing options are checked on integration and mass impact.

The challenge of this design is finding a suitable combination of different wing shapes which achieve a sufficiently high trimmed subsonic L/D of around 6, acceptable landing speed but also being fully trimable in hypersonic flight at high-angles of attack. The dry weight of this SLB8 variant should be in the range of SLB7 (see Table 4), or preferably less, and mechanical integration should be feasible.

A multi-disciplinary design analysis (MDA) including subsonic as well as hypersonic aerodynamics, structural pre-design and mass estimation and reentry flight dynamics are to be considered. The complexity of the necessary wing deployment mechanisms should be at a minimum and its protection against hot gas flow at Mach 10 is to be assured.

The wing geometry parameters and the wing position with respect to the fuselage are offering several degrees of freedom to the design. Moreover, the impact of parameter variation on the different disciplines is strongly coupled. E.g. wing geometry is affecting mass and vehicle CoG-position while both impact flight dynamic behavior and trimming. A partially automatic variation of parameters has been implemented in an MDA approach in order to systematically search for feasible and promising lay-outs (see below!).

Variable geometry wings in aeronautics have been under investigation at least since the mid of the 20th century and numerous concepts and operational aircraft have been studied and realized [15, 16]. RLV first stages with variable wings have been studied in the USSR in the context of Energia Buran and later also in DLR [17].

The SLB8-V3 includes an inner fixed part of the wing comparable in size and geometry to the V2 which generates sufficient lift in hypersonic, high AoA flight. Bow-shock interaction with the outboard leading edge as for SLB7 [13] can be avoided and biplane flow effects during ascent are reduced. A sweep and a foldable design are the studied options for the outer variable part of the wing. A variable sweep wing configuration has been selected which in its stored position is only partially protected by the fixed segment and the tip section extending backwards (Figure 6, top). This preliminary version of SLB8V3 has a span of 46 m in deployed configuration Figure 6, bottom) whereas in folded condition the span is 26.4 m. Trimming of the vehicle in the hypersonics is shown to be possible for an AoA range of 20° to 50° and maximum trimmed subsonic glide ratio is calculated at 5.6 for Mach number of 0.4.

The integration of the outer wing segment inside the inner part is essential for the technical feasibility and has been preliminarily analyzed in CAD (Figure 7). The connecting and pivot-point of the outer part is positioned behind the leading edge box close to the maximum thickness of the fixed inner airfoil. The trailing edge of the inner part is kept open to allow the sweeping part to be stored. Consequently, instead of trailing edge flaps the inner segment has separate spoilers on its lower and upper surface.

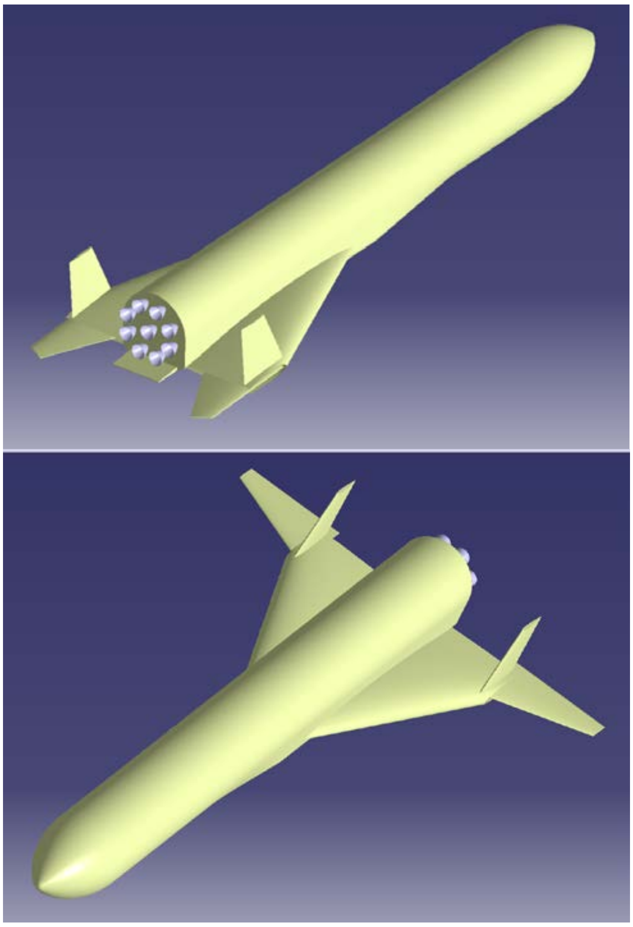

Figure 6: SLB8-V3 design option in hypersonic reentry (top) and subsonic cruise (bottom)

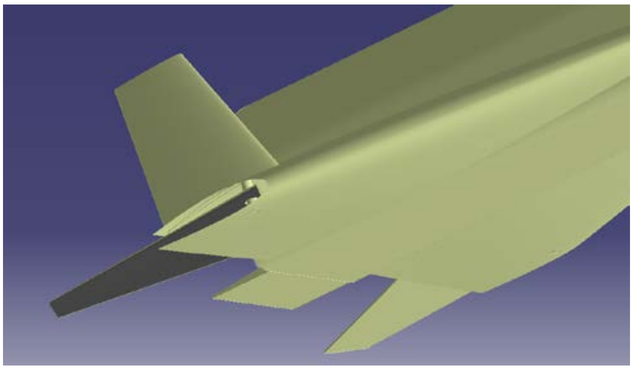

Figure 7: Preliminary design of SLB8-V3 outboard wing integration

The promising preliminary design from the above stated wing variation study is used as a benchmark in an automated parametric study tool called *SART-toolbox*. The geometric aspects of wing design are given a certain range within which random samples are generated. This data when put together generates different wing geometries, which are put through a series of analysis tools for the selection of best possible models. First, the mass properties are calculated for each model. Then, a preliminary analysis is performed to study the aerodynamic properties in the subsonic regime. Lastly, the aerodynamic properties are analyzed in the hypersonic regime. This is done to identify configurations that are trimmed for both subsonic and hypersonic flights.

Figure 8 shows the scatter plot of 1000 geometry options compared based on empty mass, wing span and maximum cruise lift-to-drag ratio. The end goal is to narrow down the search space by identifying trimmed configurations with lower mass (comparable to SLB7) and not too large wing spans to avoid shock interaction in the hypersonic regime. A good lift-to-drag ratio (above 6) in the subsonic regime is also desirable to facilitate in-air-capturing and consequently, successful retrieval of the booster. Through this preliminary variation study, multiple feasible design options can be identified and a detailed study can be performed to select the best possible one.

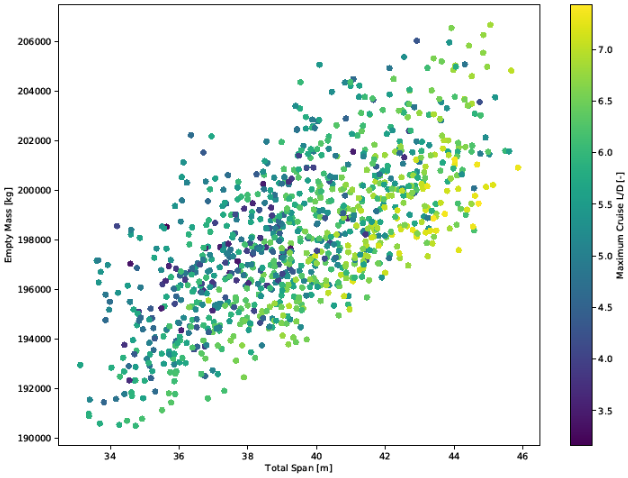

Figure 8: SLB8 parameter variation output *SART-toolbox*

Although promising configurations are found, the SLB8-V3 is still not frozen and enhanced mass estimations of the deployment mechanisms are to be performed.

5 ASCENT FLIGHT CONTROL

Simulated 6DOF ascent trajectories are used to analyze behavior of the Thrust Vector Control system in case of wind and gusts interacting with the winged configuration in nominal and off-nominal conditions. The passenger reference mission from Australia to Europe has been considered as the baseline for all simulation cases. Besides the nominal ascent profile also ascent trajectories under the influence of the operational anomalies with reduced Isp resp. thrust and engine-out cases are investigated.

5.1 Reference mission Australia – Europe

The ambitious Australia – Europe mission has been used as the reference case since the beginning of the SpaceLiner investigations [3 - 5]. This flight distance should be served for 50 passengers on a daily basis in each direction. Several other, shorter intercontinental missions exist. Flight path as well as groundtrack constraints and demands for operationally interesting launch and landing sites influence the selection of practical reference trajectories. The launch and ascent noise as well as the sonic boom reaching ground are most critical for a viable SpaceLiner operation in the future.

As a preliminary and currently non-binding assumption, the flight connection Europe – Australia and its return route is assumed for two on-shore launch landing sites located in Queensland, Eastern Australia and in the German North-Sea-coastal region. Both locations have the advantage of the complete launch ascent and supersonic gliding approach capable of being performed over the sea while still being relatively close to each continent's major business centers. These are two key-requirements for successful future SpaceLiner operation.

The descent ground track of the nominal reference mission is shown in e.g. [12]. Noise and sonic boom impact on inhabited areas is very low and actual proof of full public acceptability of the vehicle flying at very high altitude is under assessment. The propulsive phase of approximately 8 minutes duration is directly followed by hypersonic gliding succeeded by landing approach after approximately an additional hour and 20 minutes of flight. Within the Phase A analyses of the SpaceLiner project the nominal ascent profile for the reference mission, as well as off-nominal ascent trajectories under the influence of atmospheric disturbances and operational anomalies have been simulated in 3DOF and 6DOF [18]:

- Nominal undisturbed ascent trajectory
- Ascent trajectories with atmospheric disturbances
  - Large scale wind profile (HWM93)
  - Moderate stochastic gusts (Karman)
  - Combined disturbances (HWM93 & Karman)
- Ascent trajectories under anomaly scenarios
  - Reduced Isp of the booster's SLMEs by -3 s
  - Premature stage separation at nominal -6.5 s
  - Failure of outermost SLME at Lift-Off
  - Failure of outermost SLME at Max-q

5.2 Disturbed ascent with wind and gusts

The most critical disturbed ascent scenario with wind and gusts (HWM93 & Karman) assesses the combined impact of global and local atmospheric disturbances on the nominal ascent trajectory. The nominal undisturbed ascent path is used as the command signal for the flight control system. While TVC-deflections in vertical (pitch) directions are mostly driven by the CoG movement and subsequent engine cut-offs, the lateral deflections are influenced by wind (Figure 9). Maximum angles remain within 2.5°; well within the capabilities of TVC. Note roll control is devoted only to the two SLP engines.

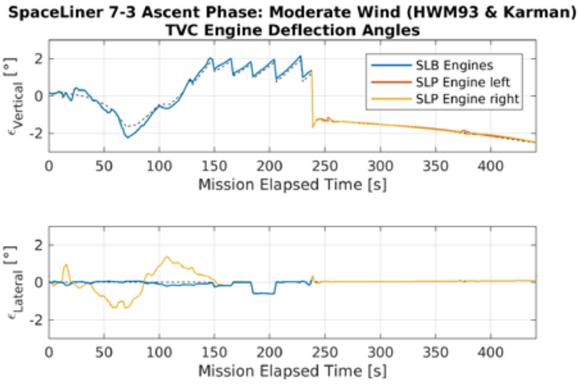

Figure 9: TVC deflections of ascent trajectory for wind and gust scenario; dashed line indicates static trim condition [18]

5.3 Engine anomaly and atmospheric disturbance

Three off-nominal cases have been simulated [13, 18]: Engine I_{sp} degraded by 3 s under all conditions (equivalent to c*-reduction of 29.4 m/s). In a conservative approach the assumption is that all engines are affected. Further, premature separation of SLB is regarded, assuming its ascent propellant reduced by 20 tons. The third off-nominal case is the impact of the outmost SLB-engine inoperative; either from lift-off or starting maximum dynamic pressure. Flight times are slightly increased and realized ground tracks are somewhat altered. However, in all investigated cases the mission success has been demonstrated even under significantly degraded off-nominal conditions [13, 18].

An unplanned SLB outboard SLME shut-down immediately before reaching maximum dynamic pressure is the yet most critical control condition investigated due to the relatively strong atmospheric disturbances acting on the RLV in this phase. A newly computed 3DOF anomaly ascent path is used as the new command signal for the flight control system. The impact of the engine anomaly on the vehicle's control deflections is clearly visible in Figure 10 when comparing with Figure 9. However, even under this severe failure condition the remaining deflection margin is more than 200% with respect to the limit of 8°, demonstrating once again the robust philosophy.

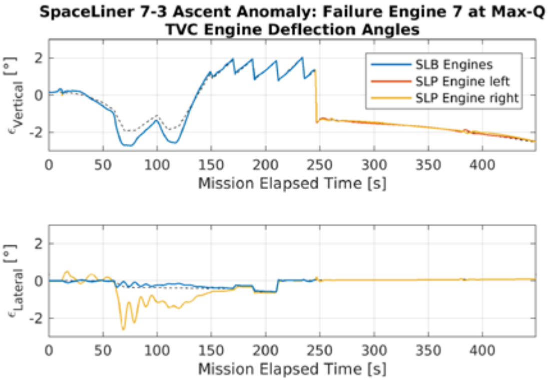

Figure 10: TVC deflections of ascent trajectory for combined SLME anomaly and wind and gust scenario; dashed line indicates static trim condition [18]

6 CONCLUSION

The DLR proposed reusable winged rocket SpaceLiner for very high-speed intercontinental passenger transport has successfully completed its Mission Requirements Review (MRR) and is progressing in its conceptual design phase. Assuming advanced but not exotic technologies, a vertically launched rocket powered two stage space vehicle is able to transport about 50 passengers over distances of up to 17000 km in about 1.5 hours.

The passenger rescue capsule, designed to be used in cases of extreme emergencies, has been subjected to systematic multi-body simulations of the capsule separation in different flight conditions. While in the majority of the investigated cases the separation maneuver behaves as expected, preliminary results indicate that SLC separation at maximum dynamic pressure in ascent is highly critical and might not be feasible. Analyses are ongoing in a systems engineering approach to obtain more data for design improvements, leading to the next iteration step, the SpaceLiner 8.

Studies for options to adapt the large unmanned booster stage are currently under way with a swept-wing design showing some promising results. Simulated 6DOF ascent trajectories demonstrate the robust behavior of the Thrust Vector Control system showing significant margins even in case of wind interacting with the winged RLV combined with anomaly case on one engine lost.

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