The SpaceLiner Hypersonic System – Aerothermodynamic Requirements and Design Process

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The revolutionary ultrafast passenger transport SpaceLiner is under investigation at DLR since 2005. The two-stage, fully reusable vehicle is powered by rocket engines. The maximum achieved velocity, depending on the configuration or mission type, is beyond 7 km/s putting some challenging aerothermal requirements on the vehicle. At the lower end of the speed-range, the SpaceLiner should have the smallest possible flight velocity for landing with an acceptable angle of attack.

This paper describes the technical status achieved for the most recent SpaceLiner 7 configuration. The focus is on all system aspects of the reference vehicle's preliminary design including the SpaceLiner's nominal trajectory and flight performance which have an impact on the aerodynamic configuration. Major design requirements are defined.

An overview on the aerodynamic database established by numerical calculations of the four different flyable configurations (both stages, launch configuration, emergency passenger capsule) in the complete, broad Mach-number range is provided.

Nomenclature

D	Drag	N
L	Lift	N
M	Mach-number	-
g	gravity acceleration	m/s^2
q	dynamic pressure	Pa
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-

Subscripts, Abbreviations

AOA	Angle of Attack
CMC	Ceramic Matrix Composites
GLOW	Gross Lift-Off Mass
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
RLV	Reusable Launch Vehicle
TPS	Thermal Protection System
cog	center of gravity
cop	center of pressure

1 INTRODUCTION

A strategic vision has been proposed by DLR in 2005 which ultimately has the potential to enable sustainable low-cost space transportation to orbit (references 1, 2, 3). Ultra long distance travel from one major business center of the world to another major agglomeration on earth is a huge and major market. The ultra-fast transportation far in excess of supersonic and even potential hypersonic airplanes is definitely a fundamental new application for launch vehicles.

Such a new kind of 'space tourism' based on a two stage RLV has been proposed by DLR under the name **SpaceLiner** [1]. Ultra long-haul distances like Europe – Australia could be flown in 90 minutes. Other interesting intercontinental destinations between e.g. East-Asia and Europe or the Trans-Pacific-route to North-West America could be reduced to flight times of slightly more than one hour [7, 13].

Figure 1: The SpaceLiner vision of a rocket-propelled intercontinental passenger transport is one of the most challenging projects in hypersonic research

2 THE SPACELINER CONCEPT

The general baseline design concept consists of a fully reusable booster and passenger stage arranged in parallel. All rocket engines should work from lift-off until MECO. A propellant crossfeed from the booster to the passenger stage (also called orbiter) is foreseen up to separation to reduce the overall size of the configuration. After fast acceleration to its maximum speed the hypersonic transport is gliding for the remaining more than one hour flight to its destination.

2.1 Status of Previous Technical Development

First proposed in 2005 [1], the SpaceLiner is under constant development and descriptions of some major updates have been published since then [2, 5, 6, 7, 12, 13]. The European Union's 7th Research Framework Programme has supported several important aspects of multidisciplinary and multinational cooperation in the projects FAST20XX [11], CHATT [11], HIKARI, and HYPMOCES [22]. Thus, significant advances since the paper of the last aero-thermodynamics symposium [10] are to be reported.

Different configurations in terms of propellant combinations, staging, aerodynamic shapes, and structural architectures have been analyzed. A subsequent configuration numbering has been established for all those types investigated in sufficient level of detail. The genealogy of the different SpaceLiner versions is shown in Figure 2. The box is marking the configuration trade-offs performed in FAST20XX in 2009/10.

These configuration studies supported the definition of the current reference configuration SpaceLiner 7. The designs of the interim research configurations 3, 4, 5, and 6, despite not fully studied in all details have been iteratively sized with careful scaling of the reference mass break-down, preliminary aerodynamic sizing and always trajectory optimization. An overview on these configurations can be found in [6].

At the end of 2012 with conclusion of FAST20XX the SpaceLiner 7 reached its first consolidated technical status. Several subsystems are sized and integrated, early operational scenarios are established, and cost and potential business cases are assessed. At the same time the design is further refined and meanwhile the third subversion called 7-3 is reached.

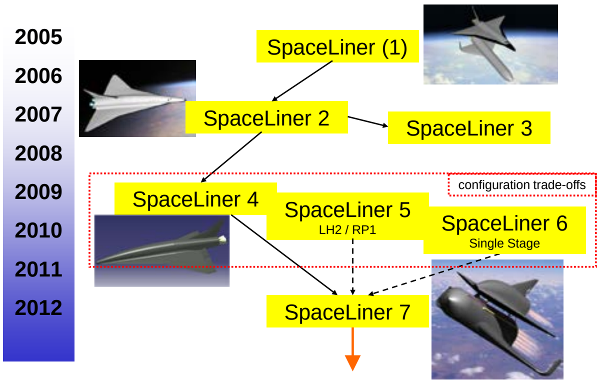

Figure 2: Evolution of the SpaceLiner concept

2.2 Technical Description of the SpaceLiner 7 Configuration

The current arrangement of the two RLV-stages at lift-off is presented in Figure 3. Stage attachments are following a classical tripod design. The axial thrust of the booster is introduced through the forward attachment from the booster intertank into the nose gear connection structure of the orbiter. The aft attachment takes all side and maneuvering loads. The option of a belly to belly connection is not preferred for two reasons: A strong unintended aerodynamic interaction of the two wings and because propellant crossfeed lines on the booster would be directly affected by the hypersonic flow during reentry of this stage. All LOX-feedlines and the LH2-crossfeed connection are attached on the booster's top outer side, thus, subjected to flow in the relatively cold wake region. The feedlines of the upper stage are completely internal and ducted underneath the TPS.

The arrangement in Figure 3 is the current baseline, however, it is still subject to trade-offs and optimization and hence might be changed in the future.

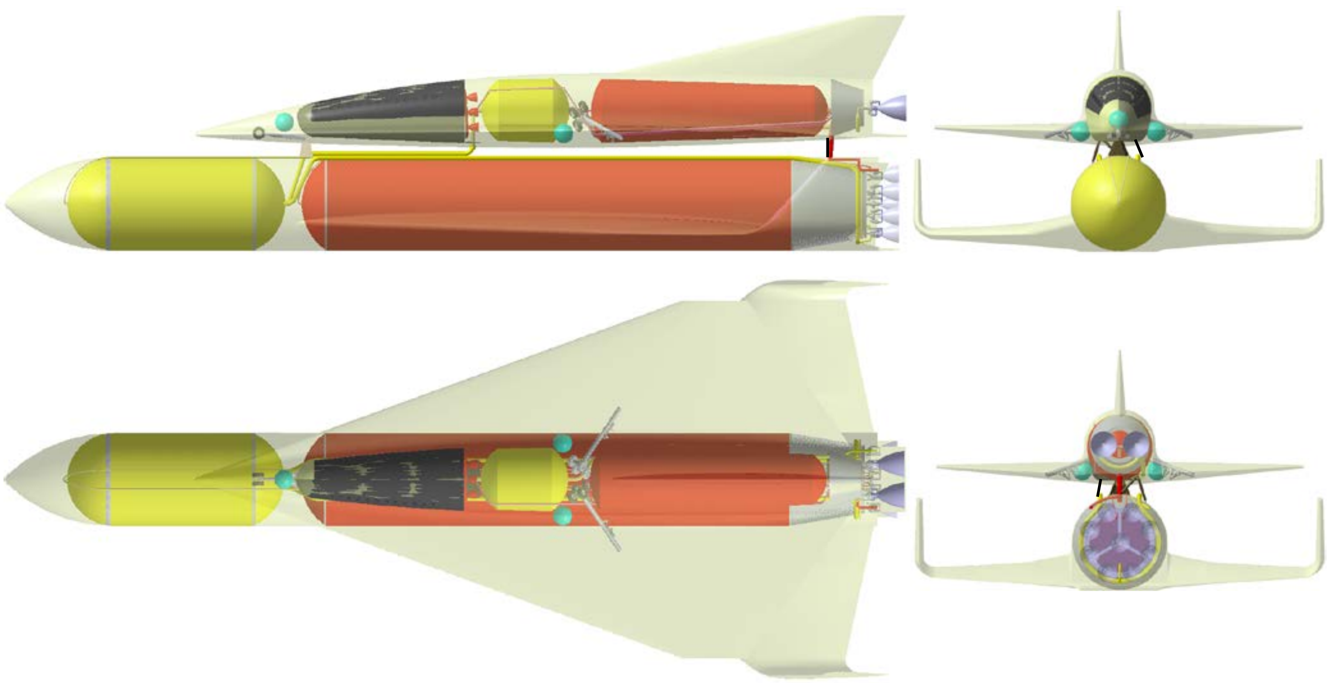

Figure 3: Sketch of the SpaceLiner 7-3 launch configuration with passenger stage on top and booster stage at the bottom position

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 7-3 passenger stage

length [m]	span [m]	height [m]	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

Since the beginning of the SpaceLiner investigations the reusable booster stage has always been somewhat in the shadow of the orbiter which is carrying the passengers and is experiencing the highest thermal loads and reaching maximum velocity and altitude. However, the booster is also a very high performance launch vehicle stage and critical to the overall success of the SpaceLiner configuration.

Recently an update of the winged reusable booster stage has been defined based on extensive analyses of the propellant crossfeed system, pre-design of major structural parts like tanks, intertank and the thrust frame. Further, the size of the body flap and the geometry of the large wing were optimized.

The passenger cabin of the SpaceLiner has a double role. Providing first a comfortable pressurized travel compartment which allows for horizontal entrance of the passengers, the cabin in its second role serves 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 is required to fly autonomously back to Earth's surface in all separation conditions. 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. The capsule's configuration resulting from work in FAST20XX is depicted in Figure 4.

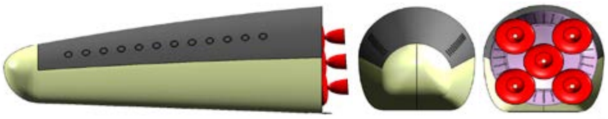

Figure 4: SpaceLiner7 reference passenger capsule design in side-, front-, and aft-view

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. The current requirement of capsule separation being feasible at any flight condition and attitude is highly challenging from a technical point of view. Recent analyses revealed some critical issues to be addressed in order to improve the safe functionality of the cabin rescue system. Alternative capsule integration concepts have been proposed and technically analyzed [24]. However, each of the explored design options is linked to severe challenges and drawbacks. Further investigations are necessary to find a promising and reliable system.

In four critical flight points the abort trajectory has been simulated, demonstrating that after successful separation the SpaceLiner7 capsule is able to fly safely back to Earth during any perceived abort scenario:

- Launch pad
- Booster separation
- Highest altitude of the SpaceLiner7 orbiter
- Main engine cut-off (MECO)

Some results of these trajectory simulations are presented in reference 24.

A highly innovative investigation on design options to improve the capsules flight performance after separation is ongoing in the FP7-project HYPMOCES aiming to investigate and develop the technologies in the area of control, structures, aerothermodynamics, mission and system required to enable the use of morphing structures [22, 23]. Inflatable as well as rigid deployable wing options are under study. The baseline design after finishing the first design loop is shown in Figure 5. Similarities and major differences are visible in comparison to the reference geometry of Figure 4.

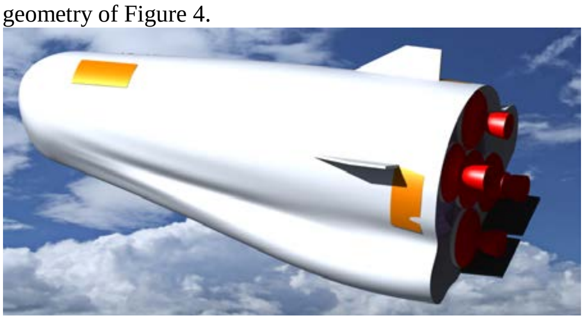

Figure 5: SpaceLiner capsule option with inflatable morphing lower section and deployable fins

The SpaceLiner passenger capsule with its shape and integration issues is currently in a dynamic design loop. Future evolutions of the SpaceLiner configurations will strongly be influenced by the obtained results.

2.3 Definition of SpaceLiner 7-3 Aerodynamic Configuration

The Mach number range of the SpaceLiner passenger stage stretches from the hypersonics through the transonic regime to the low speed subsonic landing approach. Safe controllability of the vehicle in all flight conditions has to be assured including during abort cases.

The SpaceLiner 7 is the first SpaceLiner configuration characterized by an aerodynamic shape arisen from a fully automated optimization process. In order to consider a wide range of the hypersonic trajectory, three points with different flight Mach numbers (20.1, 13.6, 6.0) and corresponding altitudes were chosen for the optimization. The final result of the optimizations, a trade-off between the optima of the three trajectory points, showed considerable improvements in glide ratio and heat loads and pointed out the clear advantages of a single delta wing [12].

The shape optimization resulted in a trailing edge angle which affects the center of pressure position in a way that the pitching moment at maximum L/D hypersonic flight is very close to its trimmed state without any significant control surface deflection. Thus, the optimum gliding efficiency and hence range is achieved. A vertical stabilizer with very large leading edge inclination has been chosen [13]. The resulting shape of the SpaceLiner 7 passenger stage wing and body in top view is shown in Figure 6. The SpaceLiner's wing flaps' definition is based on the most extreme flight maneuvers to be expected: an abort scenario starting at the time of booster separation with the passenger stage's propulsion system inoperative. The flap's hinge line attachment is influenced by the Space Shuttle example. The overall design will be subject to a more detailed assessment of efficiency and aerothermodynamic issues in the future.

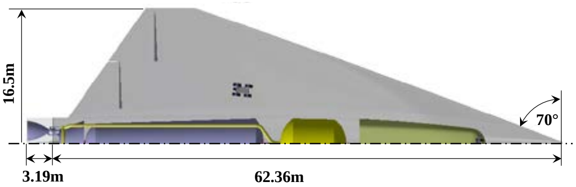

Figure 6: SpaceLiner 7 orbiter wing geometry characteristics

The SpaceLiner Orbiter wing airfoils were slightly adapted for the latest 7-3 configuration to keep a finite minimum thickness at the trailing edges. For operational considerations and for practical TPS integration a 50 mm constant thickness is chosen.

At the wing's root a modified NACA 66-003.5 is implemented which is cut when the trailing edge thickness reaches 50 mm. At the wing tip a modified NACA 66-005.5 is cut at the same trailing edge thickness. The relative airfoil thickness in between is linearly interpolated.

Although the changes in trailing edge thickness are minor, having almost no impact on calculated aerodynamic performances, the fuselage-wing interface surface geometry with complicated 3D-shapes needed a redesign. The local curvature is carefully designed to avoid any potential hot spot areas.

Major geometry data of the SpaceLiner 7-3 passenger stage are summarized in Table 2.

Also the SpaceLiner booster stage has to operate in a huge Mach number range, stretching from the hypersonics through the transonic regime to the low speed subsonic landing approach. In the aerodynamically controlled flight after MECO the stage's cog is located far to the rear due to empty tanks in the forward sections and nine rocket engines mounted in the back. The shape resulting from several system trade-offs for the SpaceLiner7 booster stage wing and body is shown in Figure 7 in view from the bottom side. Note a high leading edge sweep of 82° at the inboard strakes which is reduced to about 43° outboard. Major geometry data of the SpaceLiner 7-3 booster stage are summarized in Table 1.

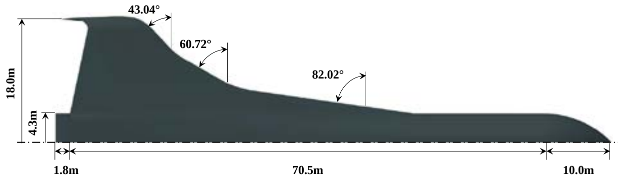

Figure 7: SpaceLiner 7-3 booster wing geometry characteristics

The booster wing (and winglet) airfoils have been adapted from the previous version 7-2. A constant trailing edge thickness of 75 mm is chosen. The original 4-digit NACA wing airfoils have been altered to a different geometry, delivering aerodynamic as well as structural advantages. The maximum thickness position on the chord line is moved backwards which is beneficial for drag reduction in the supersonic and hypersonic flow and at the same time allows for larger frame heights in those regions where the largest amount of the aerodynamic lift forces are introduced. The wing modifications also resulted in a constant trailing edge sweep.

Four reference sections are defined and the intermediate areas are interpolated. The airfoil changes from configuration 7-2 to the latest 7-3 are:

- Wing root: NACA 1406 to modified NPL-EC/ECH 4.5 cut at trailing edge thickness of 75 mm
- Wing mid1: NACA 2407 to modified NPL-EC/ECH 7.0 cut at trailing edge thickness of 75 mm
- Wing mid2: NACA 2408 to modified NPL-EC/ECH 8.0 cut at trailing edge thickness of 75 mm
- Wing tip: NACA 2410 to modified NPL-EC/ECH 10.0 cut at trailing edge thickness of 75 mm

The shapes of the NPL airfoils were defined by algebraic formulae at the National Physical Laboratories in the UK. They comprise an elliptic forward portion (E) and a rear portion (C) which, in the case of ECH, is replaced by a hyperbolic (H) curve very near the trailing edge [14].

The changes of the wing airfoils to NPL resulted in a slight decrease of drag and improved L/D compared to the previous 4-digit NACA foil wing.

2.4 Aerothermodynamics, Thermal protection and active cooling subsystem

The ambitious Australia to Europe reference mission requires the SpaceLiner passenger stage to accelerate to a maximum speed slightly above 7 km/s. In the subsequent hypersonic gliding trajectory the vehicle surface at the lower side and leading edges are subject to severe thermal conditions. Maximum calculated radiation adiabatic surface temperatures would reach about 2600 K and heat fluxes about 2 MW/m^2 [21].

The preliminary sizing of the SpaceLiner7's Thermal Protection System (TPS) has been carried out for several different heat loads according to nominal flight and also for different abort cases. To be able to determine the heat loads for a full vehicle surface along different trajectories, fast engineering methods have to be used. A fully turbulent flow along the flight path has been assumed for the TPS dimensioning as a conservative assumption.

Due to the requirement of reusability, only non-ablative materials are suitable on the SpaceLiner's surface. According to the different maximum temperatures occurring at the different surface areas, different materials are chosen [16, 21].

The maximum acceptable temperature for the passive TPS is limited to approximately 1850 K to be compliant with the reusability requirement. The structure underneath is allowed to heat up to maximum temperatures between 400 K and 530 K depending on the selected materials.

This leads to a total TPS mass on the passenger stage (without capsule and tank insulation and system mass margin) between approximately 15.5 tons (530 K substructure temperature) and 24.6 tons (400 K) [21]. This is a significant mass saving compared to the previous SpaceLiner 7-2 TPS layout [7, 16]. Recently an alternative TPS on the vehicle's upper surface has also been considered, consisting of two layers of a metallic skin. Although significantly heavier than thermal blankets it should be operationally more robust [21]. The heat insulation on the passenger capsule alone, including an ablatable nose, is approximately 4000 kg [21]. In a similar design procedure the TPS of the reusable booster stage has been defined. Large upper surface areas are to be covered by thermal blankets. The booster's TPS mass reaches approximately 13.9 tons (without cryogenic tank insulation and margins) [21].

The leading edge and nose areas exceed the limit of 1850 K acceptable by CMC and need an advanced active cooling. [2, 10, 20, 21]. In these areas an innovative method based on transpiration cooling using liquid water has been foreseen and was experimentally tested during FAST20XX in DLR's arc heated facility in Cologne using subscale probes of different porous ceramic materials [17].

Although this advanced cooling process is still at a TRL of 3, a first preliminary active cooling pre-design has been executed at DLR-SART for the SpaceLiner geometry. The transpiration of H_2O is required starting during the final phase of the powered orbiter flight when leading edge temperatures are already becoming excessively high. Besides the overall promising results also some technical challenges of the active transpiration cooling system have been detected in the FAST20XX-investigations. Precise controllability of the water flow through the porous ceramic media has been found difficult [21]. The experiments sometimes were running into over or under supply of water which could not be recovered within the same experimental run. A more sophisticated supply system would be needed in a flight vehicle. However, real flight conditions usually are more complex and demanding than those in a laboratory. Another concern is the fact that the gas flow from the coolant might trigger early boundary-layer transition. As a consequence, some areas of the passive TPS might need to be reinforced.

Therefore, the active transpiration cooling of leading edges and nose is still the reference design option but could once be replaced by other means of active cooling [20, 21]. A more detailed system assessment of the different design options based on reliable mass estimations should be performed in the next iteration steps.

2.5 Nominal trajectory

Several trajectory options have been traded for the Australia – Europe reference mission. These are all following a standard launch vehicle vertical ascent with an initial azimuth in North-Eastern direction overflying the arctic sea before approaching Europe from the North-Eastern Atlantic. This is the same baseline trajectory which has been established for the SpaceLiner 4 using ASTOS optimizations [5]. Maximum speed of the vehicle is around 7.1 km/s at 69 km and the flight path angle γ at MECO is close to 0° (Figure 8). Then the propulsive phase is followed by hypersonic gliding of more than one hour.

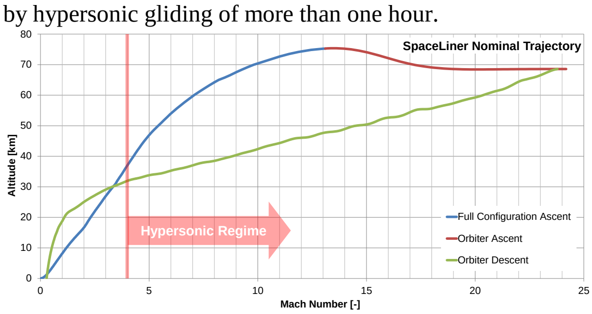

Figure 8: Nominal reference trajectory of SpaceLiner 7

An alternative option is a trajectory with a few degrees of γ in this point which would result in a ballistic arc duration of a couple of minutes for the SpaceLiner. The vehicle would travel during this phase more than 1000 km almost outside of the atmosphere at very low drag. However, in order to avoid excessive heatrates, an increased angle-of-attack is subsequently needed at lower altitude which has a strongly decelerating effect. A definitive answer on the best trajectory requires detailed system studies taking into account flight path optimization, adapted TPS-sizing, and reliable data on the drag coefficient in low atmospheric density. The Italian aeronautical research establishment CIRA's DSMC calculations and work by the University of Naples on the SpaceLiner at high altitudes [11, 18, 19] are providing realistic drag coefficients under these conditions (see also section 3.4!).

The launch and ascent noise as well as the sonic boom reaching ground are most critical for a viable SpaceLiner operation in the future. The selection of potential SpaceLiner launch and landing sites will likely be influenced by constraints due to generated noise [13]. New trajectory optimizations currently investigated take into account such constraints of a realistic operational scenario which are restrictions in acceptable flight corridors and still relative proximity of launch sites to potential customers.

3 AERODYNAMIC REFERENCE DATABASE

Aerodynamic data sets have been generated with different numerical tools and an aerodynamic database for early preliminary engineering design work has been established for all four SpaceLiner flight configurations [15]: The mated launch vehicle, the booster stage, the passenger stage, and the rescue capsule. This data base is highly useful for performance analyses in nominal and off-nominal conditions and assessment of the SpaceLiner's flying qualities [25].

Different fast engineering calculation tools were used and combined when appropriate. Complementary CFD (Euler) simulations were also conducted in the framework of the FAST20XX project.

3.1 Ascent / Launch Configuration

During the ascent, both stages, the booster and the orbiter, are connected from lift-off until stage separation. After separation, the orbiter further accelerates until its MECO.

This element of the aerodynamic database was created by a combination of semi-empirical and surface inclination methods. It is to be acknowledged that the character of these procedures does not allow for modeling complex surface geometries and the resulting fluid mechanics. For example flow interactions between different stages or vehicle components and shock-shock- or shockwave-boundary-layer-interactions cannot be modeled. To consider these issues and to validate the current reference, sophisticated CFD simulations or dedicated wind tunnel tests will have to be conducted in the future. Despite these challenges, the data as shown in Figure 9 can be very useful to accomplish the SpaceLiner's flight performance assessment.

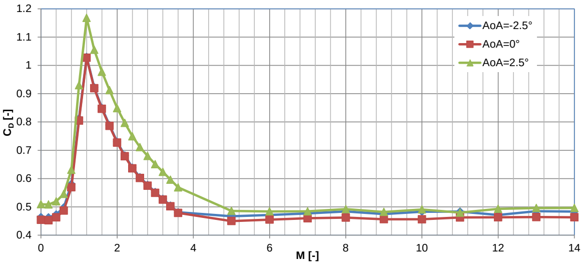

Figure 9: Reference drag coefficient for the full mated launch configuration in ascent flight [15]

3.2 Booster Descent Configuration

After booster separation, the orbiter stage further accelerates whereas the booster glides back to the earth. Two examples of the glide ratio L/D are shown in Figure 10 as a function of α for the Mach numbers 8 and 10 and different flap deflection angles.

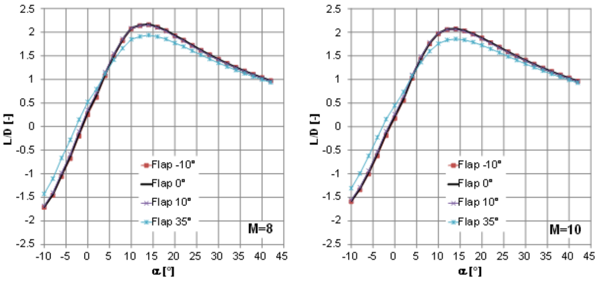

Figure 10: Lift-Drag-ratio of SpaceLiner 7-2 booster stage at M=8 and M=10 [15]

Note, that the airfoil geometry of SpaceLiner 7-2 is not the latest design but still uses the 4-digit NACA (compare previous section 2.3). The flap deflection has a strong influence on the maximum L/D, which in the full flight regime is assessed in the range of 1.2 to 2.4, depending on the deflection angle and the Mach number [15].

3.3 Orbiter Descent Configuration

For the descent flight of the orbiter stage the most detailed aerodynamic analyses of all configurations were conducted yet. In addition to fast empirically derived assessment, a panel code, and surface inclination methods also CFD (Euler) simulations were performed from subsonic to hypersonic Mach numbers.

ESA has been calculating the shape of the SpaceLiner 7-1 passenger stage with Euler CFD (Figure 12 and Figure 13). An unstructured grid with several million elements has been generated. Obtained coefficients have been used in support for establishing the aerodynamic data base. In the hypersonic flight regime these CFD lift and drag data are in very good agreement with those of engineering methods previously generated by DLR [15] which justifies the programs used in the aerodynamic optimization process mentioned in [12] and section 2.3.

The SpaceLiner 7-1 achieves without flap deflection an excellent hypersonic L/D of 3.5 up to M=14 assuming a fully turbulent boundary layer. The laminar-turbulent transition is assumed occurring at an altitude of 58 km which is around Mach 18. Figure 11 demonstrates the strong effect of boundary layer transition and by different trailing edge flap deflections on L/D. Therefore, any significant flap deflection is to be avoided in hypersonic gliding flight in order to achieve good range efficiency.

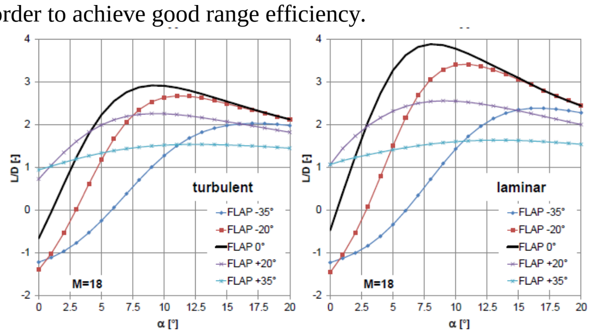

Figure 11: Lift-Drag-ratio of SpaceLiner 7-1 passenger stage at M= 18 in 58 km (fully turbulent boundary layer at left, laminar at right) [15]

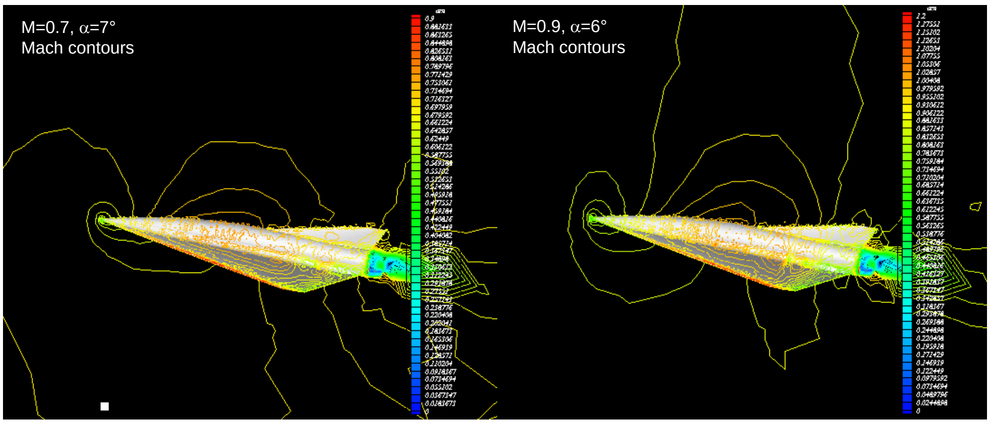

Figure 12: Mach contour plot SpaceLiner 7-1 Orbiter for M_∞=0.7, α=7° and M_∞=0.9, α=6° based on Euler CFD

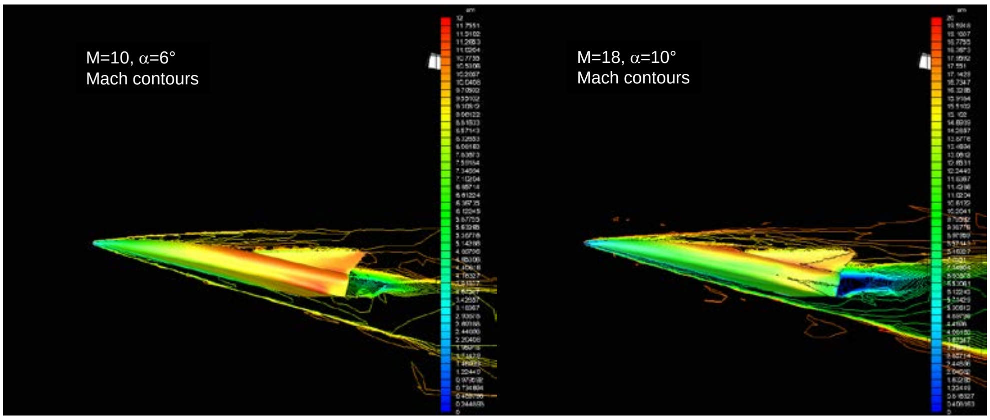

Figure 13: Mach contour plot SpaceLiner 7-1 Orbiter for M_∞=10, α=6° and M_∞=18, α=10° based on Euler CFD

3.4 Orbiter in Rarefied Flow

The range of SpaceLiner altitudes in which early rarefactions effects are expected is 75÷85 km. The inviscid conditions are based on the continuum aerodatabase, while the free molecular flow data have been computed by means of Direct Simulation Monte Carlo (DSMC). In between bridging functions are applied which deliver the altitude dependence of longitudinal aerodynamic coefficients for the 7-1 configuration [18, 19].

The DSMC code used in [19] is DS3V to compute the global aerodynamic coefficients of the SpaceLiner 7-1 with a mesh of 1961 triangles as shown in Figure 14. L/D in the rarefied regime at very high altitudes is significantly reduced compared to the continuous flow (Figure 15).

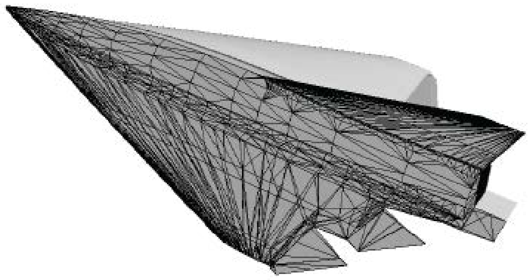

Figure 14: Unstructured body grid with deflected flaps (at -35 deg.) used in DS3V simulations [19]

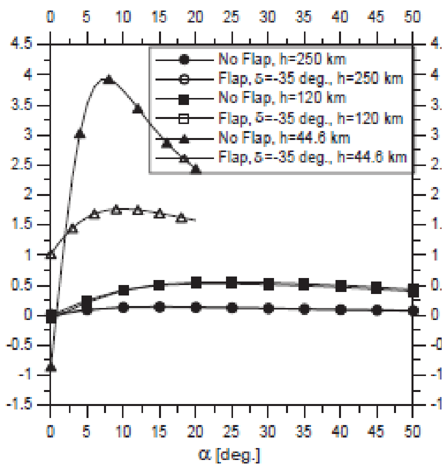

Figure 15: Lift-Drag-ratio of SpaceLiner 7-1 in comparison of continuous (44.6 km) and rarefied flow conditions [19]

4 CONCLUSION

The DLR proposed reusable winged rocket SpaceLiner for very high-speed intercontinental passenger transport is constantly maturing in its conceptual design. Research on the vehicle has been performed with support from the EU projects FAST20XX and HYPMOCES, among others, with involvement from several European partners. 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 latest iteration step of the SpaceLiner concept is the version 7 which is based on preliminary design of different subsystems and vehicle structures. An integrated, inter-disciplinary design process has delivered a convergent configuration. The paper presents the latest geometrical design of the SpaceLiner 7-3 including wing airfoil definition, the thermal protection- and active cooling sub-system, and trajectory requirements.

The aerodynamic database for early preliminary engineering design work for performance analyses in nominal and off-nominal conditions and assessment of the SpaceLiner's flying qualities is presented in a few examples.

Work on the visionary SpaceLiner concept is gaining momentum in the European aerospace community. The project puts some highly challenging questions addressing hypersonic aerothermodynamics, like safe separation of a capsule and controlled flight in the full Mach-range, in focus of future research.

5 ACKNOWLEDGEMENTS

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