The Development of the SpaceLiner Concept and its Latest Progress

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A visionary, ultrafast passenger transportation concept, proposed as the SpaceLiner, is developed by the Space Launcher System Analysis department of the German Aerospace Center DLR. Based on rocket propulsion this two stage RLV should be capable to carry about 50 passengers over ultra-long-haul distances within a fractional amount of time needed for common long-distance flights. Since the SpaceLiner has been proposed for the first time in 2005, the concept is subject to an iterative process of development. Several configuration trade-offs have been performed in order to support the definition of the next reference configuration. This paper gives a summary of the main enhancements and the knowledge gained within the preliminary design phase of the SpaceLiner orbiter stage. As the Orbiter volplanes along the major part of the hypersonic trajectory, the glide ratio is the most significant driving parameter to obtain maximum possible ranges. Thus the main focus of the investigations is on the development of an aerodynamic and aerothermodynamic shape design as well as on various system and environmental aspects or rather operating conditions which have an impact on the aerodynamic configuration.

Key Words: SpaceLiner, High Speed Passenger Transport, Hypersonic Flight, Aerodynamic Optimization, RLV

Nomenclature

A_{ref}	Reference Area
CFD	Computational Fluid Dynamics
C_D	Drag Coefficient
C_L	Lift Coefficient
C_M	Pitching Momentum Coefficient
CoG	Center of Gravity
FAST20XX	Future high-Altitude high-Speed Transport 20XX (EU funded research project)
g	Gravity Acceleration
H	Altitude
L/D	Glide Ratio
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
l_{ref}	Reference Length
M	Mach Number
RLV	Reusable Launch Vehicle
RP1	Rocket Propellant
SL	SpaceLiner
TPS	Thermal Protection System
v	Velocity
x_{ref}	Axial Position of the Reference Point
α	Angle of Attack

1. Introduction

With the SpaceLiner the DLR has proposed a visionary concept for high speed passenger transport over large distances [1],[2],[3]. Decommissioning of the Concorde leaves a break in civil supersonic passenger transport. Furthermore it can be expected that connecting large agglomerations located on different continents offers a considerable market potential for high speed passenger transport in the future.

In general the very high-speed travel option of the SpaceLiner seems most attractive for ultra-long haul distances between large business centers, at least in Australia, East Asia, Europe and the East and West Coast of North America. Reductions in total travel time of up to 80% dependent on the particular route should be feasible [4]. The ambitious westbound route from south-east Australia to central Europe is the most demanding in terms of Δv and thus chosen as the reference design case from the onset of the study.

Connecting the characteristics of space tourism with for example business travel the SpaceLiner concept has the potential to enable sustainable low-cost space transportation to orbit following a simple and conventional baseline idea: Strongly increasing the number of launches per year and hence decreasing manufacturing and operating costs of launcher systems. Therefore two main requirements are taken into account. First of all the SpaceLiner should be able to carry about 50 passengers safely along the defined reference route from Western Europe to Australia in 90 minutes. Secondly, the complete vehicle should be fully reusable. The vehicle consists of two stages, a winged booster stage and the orbiter stage including the passenger cabin. Figure 1 shows the artist's view of the SpaceLiner at the moment of separation.

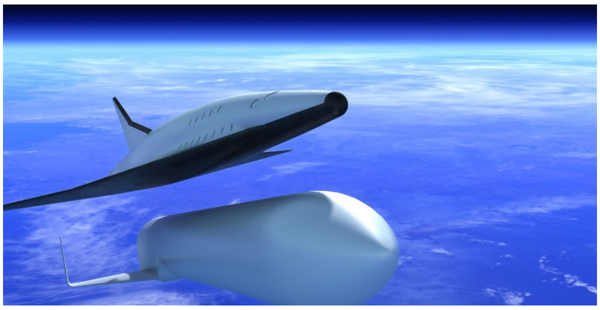


Figure 1: Artist's view of the SpaceLiner at booster separation

Since a primary characteristic of the SpaceLiner concept is the avoidance of excessively exotic technologies and equipment to enhance high reliability and safety, the booster and orbiter should be powered by rather conventional LOX/LH2 staged combustion engines. From the moment of vertical take-off to separation a propellant crossfeed from booster to orbiter is foreseen to reduce the overall size. After separation of the two stages the booster makes a controlled re-entry and will be transferred back to the launch site by the patented method called 'in air capturing', which has been investigated by DLR through simulations and has proven its principle feasibility [5],[6].
The orbiter stage further accelerates to achieve maximum altitude and velocity needed to arrive at the current destination. When the maximum velocity is reached the engines cut off and the orbiter volplanes the remaining part of the trajectory. Depending on the configuration or mission type, the maximum flight Mach numbers could reach 20 or even higher, where the consideration of aerothermal requirements becomes mandatory.

2. The Development of the SpaceLiner Configurations

Since its first proposal the SpaceLiner concept is subject to an iterative process of development. Figure 2 gives an overview of the various configurations analysed within the preliminary design phase. Technical progress has been achieved within the framework of the EU funded FAST20XX study (enframed red in Figure 2) and also by DLR internal funding.
The configurations and trade-offs have been investigated regarding to flight trajectories, structural architectures, propellant combinations, aerodynamic shape and staging. This section gives a brief description of the latest evolution up to the current version of SL7 in July 2011.
The idea of SpaceLiner started with the SpaceLiner1 and included various configurations and take-off modes which were analysed within the initial part of the preliminary design phase [3],[7],[8]. Albeit horizontal take-off is more conventional for passenger flight, unsolved problems regarding cryogenic propellant sloshing and rocket engine feeding excluded this option. Also a tandem stage arrangement was investigated but ultimately rejected due to the expected outsize length of more than 100 m and the resulting high bending loads on the structure, compared to a parallel stage arrangement length of about 60 m.

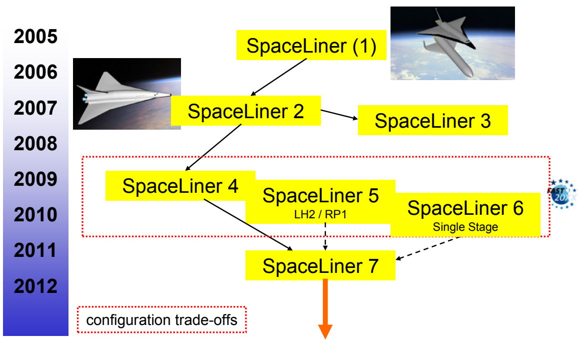


Figure 2: Evolution of the SpaceLiner concept within the preliminary design phase [9]

Safety requirements for civil passenger transport are of the utmost importance. The specific number of fatalities during the operation period should not exceed those of early jet-airliner travel which is a notable challenge in itself, far beyond the capability of today's manned spaceflight. Due to this, the rocket engines are intentionally designed below their technical limits to improve their reliability and to overcome the safety deficits of current state-of-the-art launchers. Intensive testing and

qualification of the propulsion system is further necessary. Despite all effort, tight margins are intrinsic to all launch systems and significantly reduce the achievable safety and reliability. A passenger rescue system will be absolutely essential.
Since the SpaceLiner1 denotes merely the idea of the project itself, the technical evolution of the concept is based on configuration 2 status of 2007 described for the first time in [10] and shown in Figure 3a). This baseline configuration features two engines for the orbiter and eight engines for the booster. More information about all configurations can be found in [3].

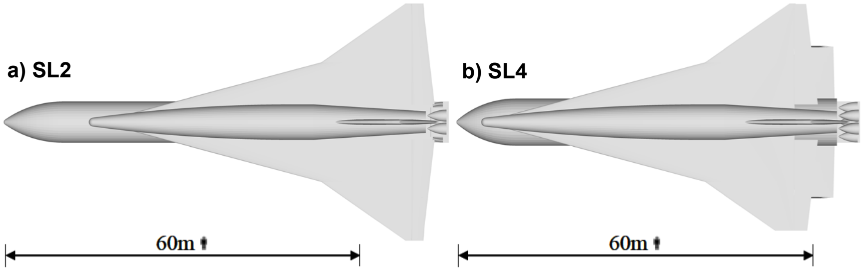


Figure 3: Upside view of SpaceLiner2 (a) and SpaceLiner4 (b) configuration, orbiter mounted on booster

Intensive research has been performed on configuration 2 and several configuration trade-offs have been implemented in order to support the definition of the next reference configuration already dubbed “SpaceLiner7”. However it can be stated that SL2, SL4 and SL7 are most intensely studied and the investigations of SL2 and SL4 have been continued until the next reference configuration crystallized. The configurations of SL2 and SL4 are similar to some extent (Figure 3). The main difference is the fact that the trim drag of SL4 has been taken into account more accurately compared to SL2. In order to minimize losses in L/D during the hypersonic flight regime, the wing has been moved forward. Iterative sizing resulted in a slight increase to Δv, implications of which require an additional booster engine and increased propellant mass of 77 tons. To account for this, the booster diameter has also been increased, resulting in a shorter booster than used for the SL2. The new aerodynamic datasets are documented in [7],[8].
The SL3 has only been an interim configuration with a slightly increased wing surface area and large winglets instead of the central fin (see Figure 4a). Although the total mass is reduced this way, the effectiveness of the winglets is questionable. Furthermore the thinness of the winglet profile causes critical mechanical and thermal loads. Hence the investigation of SL3 has been discontinued.
The SpaceLiner5 (Figure 4b) orbiter is fully identical to the SL4 configuration. Changes are only conducted with respect to the booster stage, where LOX/RP1 are now used as propellants. The higher density of kerosene should result in a smaller booster compared to LH2 while the specific impulse of LOX/RP1 is considerably lower which causes an increase of total lift-off-weight. As the orbiter remains unchanged and propellant crossfeed is still foreseen until separation, the booster also has to be equipped with a LH2 tank to feed the orbiter engines. All things considered the total propellant mass has increased by 262 tons, while the booster empty weight is reduced by 9.4 tons. The system complexity has been increased due to the different engine and propellant types on both booster and orbiter. Beyond that, the usage of kerosene would undermine the environmental friendliness of LOX/LH2 propulsion.

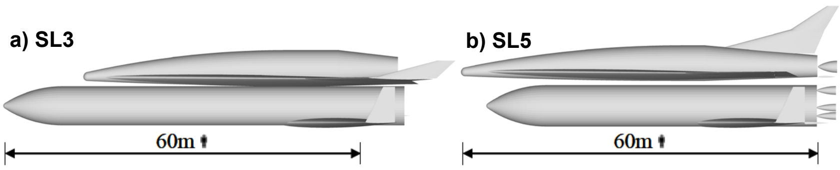


Figure 4: Side view of SpaceLiner3 (a) and SpaceLiner5 (b) configuration (SL3 pictured without engines)

Another field of research was the analysis of a single stage configuration, the SpaceLiner6 (Figure 5a), which is considerably preferable from the operational point of view.

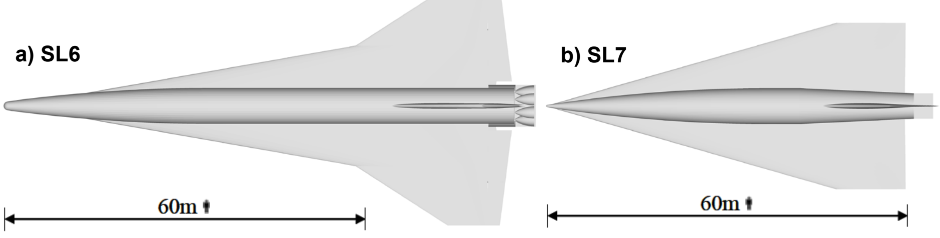


Figure 5: Upside view of SpaceLiner6 (a) and SpaceLiner7 (b), SL7 pictured without engines and booster

Previous investigations had already shown that the extremely challenging requirements of the westbound route from Australia to Europe would result in a very large and outsize stage, hence another meaningful reference mission has been chosen for these analyses; the flight from Western Europe to the Atlantic Coast of the USA, carrying 50 passengers. Based on the analyses performed, the resulting orbiter was 85 m long, required 452 tons of LOX/LH2 for its six, instead of two engines, and had a take-

off mass of 610 tons. Given that the dimensions for the single stage craft on the shorter reference route were so excessive, the single staged SL configuration for the original reference route from Australia to Europe is rendered as entirely unattractive, since in this case it is reasonable to presume that the SL dimensions would need to further increase.
Based on the experience gained from earlier configurations, the SpaceLiner7 seems to be the actual most promising configuration. The double-delta wing of all previous setups has been replaced by a single-delta to reduce thermal loads and wave drag within the hypersonic flight regime. Further reduction of the drag was achieved by decreasing the nose radius. It can also be assumed, that the single-delta configuration brings advantages regarding structural loads [11]. Interdisciplinary studies have already been conducted in terms of SpaceLiner7 and will be continued in the future.

3. Latest Progress of the SpaceLiner Concept

The latest research on the SpaceLiner Concept mainly addresses the improvement of the orbiter stage. As the previous investigations offered a lot of knowledge about system requirements, aero-/thermodynamics and operating conditions, the actual version of the SpaceLiner7 is the most detailed and elaborated conceptual design within the entire preliminary design phase. The results of recent studies are presented below in the following sections.

3.1. Flight Trajectory

In the beginning of the SpaceLiner concept the trajectory optimization was driven by reducing the fuel consumption. To address this objective a skipping trajectory seemed most advantageous. Because of high Mach numbers occurring at low altitudes, the main drawback of this trajectory is the extreme heat flux which results in a heavier and more complex TPS (Thermal Protection System). Recent TPS analyses have shown that the mass of the TPS and hence its influence on the total take-off weight is much higher than it was assumed during the previous investigations. To account for this, a Pareto optimization was conducted. Considering the fuel consumption as well as the heat fluxes, an optimized trajectory was found, where skipping did not occur anymore. Hereby the maximum heat flux and the dynamic pressure were reduced up to 50% (Figure 6), which allows for a much lighter TPS. Detailed information can be found in [12].

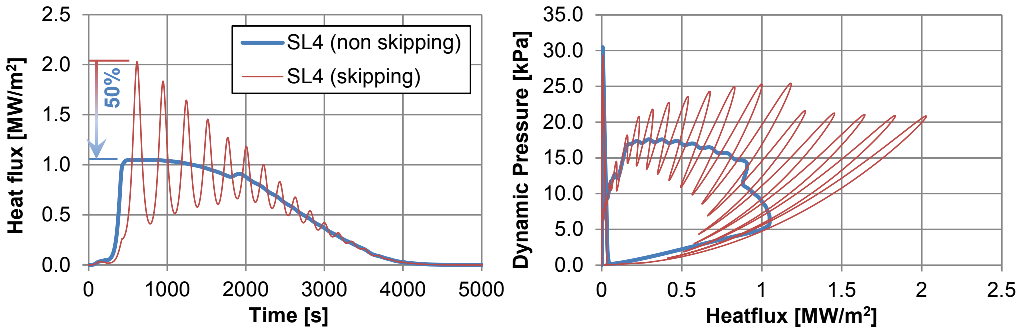


Figure 6: Reduction of maximum heat flux by avoiding skips along the trajectory

Thus no more research is done regarding to the skipping trajectory. Instead, further investigations are conducted to improve the non-skipping trajectory in terms of SpaceLiner7. Figure 7 compares the SL4 and the most recent SL7 trajectories.

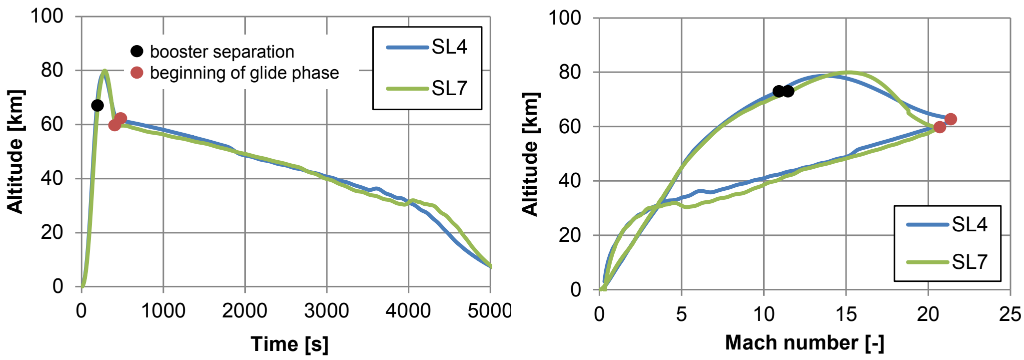


Figure 7: Comparison of SL4 and SL7 Trajectories

In case of emergency, different flight abort scenarios are investigated for the SpaceLiner4. The results are driving parameters for new designs. Within this paper, an abort is defined as failure of all engines but structural integrity and undisturbed aerodynamics with all flaps still controllable.
Two abort cases are regarded as the most important ones. The first is when the engines stop working at booster separation and the second case, when the orbiter reaches the highest altitude. Previous investigation of the center of gravity (CoG) showed that it is better for the timability when the CoG is as most backward as possible. To assure that fact, liquid oxygen (LOX) is completely dumped. In Figure 8 the abort trajectory for the first case is given as a sample. It can be seen that the limit of the acceleration

(2.5g) is not exceeded. Further investigations show that the maximum required flap deflection angles for trimming in case of flight abort are in the range of +7.5° to -7.5° which are acceptable values.

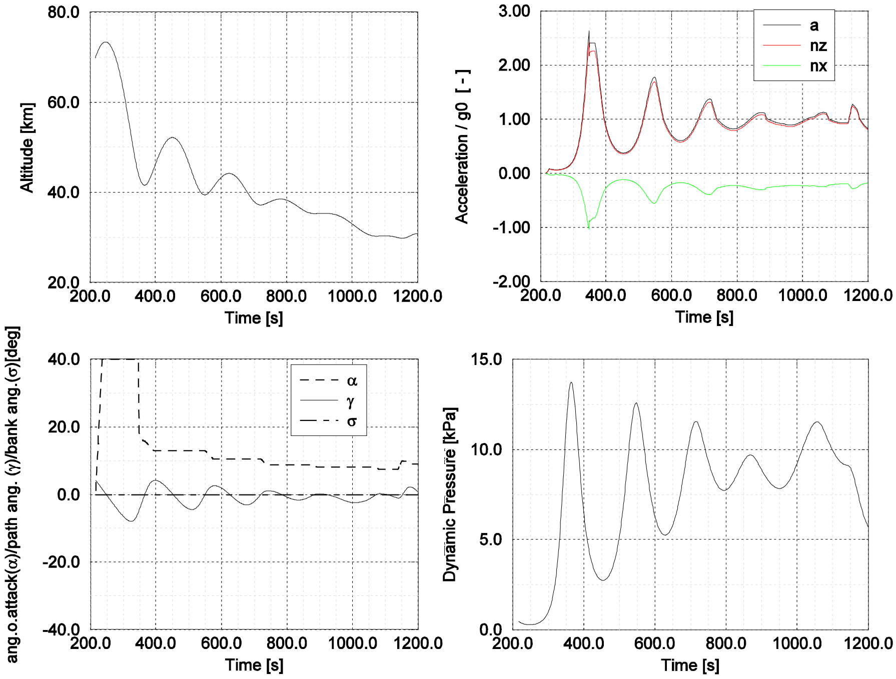


Figure 8: Results for flight abort scenario at booster separation (critical first 1000 s after separation)

3.2. Thermal Protection System

Former studies already mentioned the problem of high heat fluxes caused by the extreme compression of the hypersonic flow behind the shock waves in the stagnation regions of the SpaceLiner [13], in particular at the nose and the leading edges of wing and fin. Dependent on the nose or leading edge radius and the flown trajectory, stagnation temperatures of up to 3000 °C could occur which exceed the limits of any passive TPS.
Previous studies also demonstrated that reducing these thermal loads to a value acceptable for passive TPS only by shape modifications of nose or leading edges would dramatically corrupt the aerodynamic performance of the vehicle. Moreover an ablative heat shield would not be appropriate due to the demand of reusability.
Therefore an innovative and highly efficient transpiration cooling method was found in [14],[15] using liquid water evaporating through a porous ceramic. Experiments in the arc heated windtunnel facility of DLR have already been conducted [15] and are continued within the FAST20XX project [9]. It was shown that utilizing this cooling method can not only reduce the stagnation temperatures to harmless values but may also bring considerable savings in mass compared to active cooling using a gaseous coolant (e.g. N_2) due to the high specific heat and vaporization enthalpy of water. This might allow for decreasing the nose and leading edge radii and thus to improve the hypersonic aerodynamic performance.

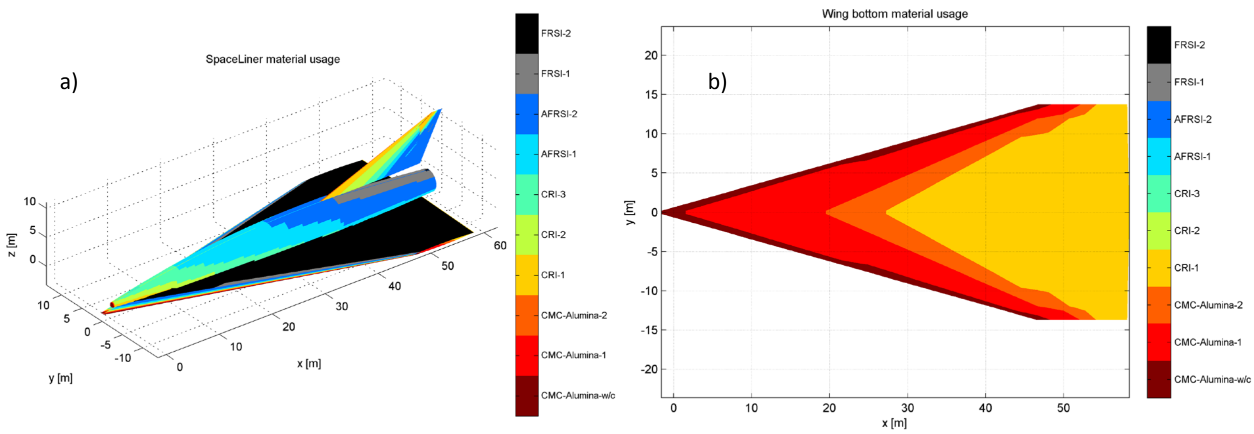


Figure 9: Temperature-dependent TPS materials distribution on the top (a) and bottom side (b) of SL7

Nevertheless active cooling is only required within thermally high stressed but spatially small regions. A passive radiation cooled TPS would suffice for the main part of the bodyshell exposed to the flow. Therefore several investigations were conducted in

terms of SL4 and an early version of SL7 to detect proper materials withstanding the temperatures arising in the different zones of the surface. The most recent results regarding SL7 (see Figure 9) are presented in the following.
The maximum acceptable temperatures for the passive TPS should be limited to approximately 1850 K to be compliant with the reusability requirement. In the high temperature zones directly behind the active cooled region, a ceramic matrix composite (CMC) cover has been selected with insulation material ZIRCAR Alumina mat. Areas with intermediate temperatures can be protected by a Conformable Reusable Insulation (CRI) which has been used for the X-37 reentry vehicle. With further decreasing surface temperatures on the topside of the vehicle the Advanced Flexible Reusable Insulation (AFRSI), also used for the Space Shuttle, can be applied. For regions below 672 K the very lightweight Felt Reusable Surface Insulation (FRSI) is selected.
More detailed information about the materials and in particular about the thicknesses, the weight and the structural integration can be found in [16].

3.3. Structural Investigations

A finite element model of the SL7 wing structure has been generated and corresponding structural analyses have been executed. The fuselage has not been investigated in detail so far. Thus, the focus of this section is on the wing structural design.

3.2.1 Wing Structural Design Requirements, Model Definition and Loads

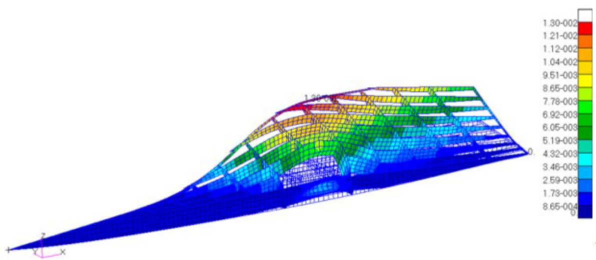
A classical spar/rib/skin design has been selected for the general layout of the wing. A main gear length of about 5 m was estimated, with four tires per main gear strut. The wing root section provides sufficient height to accommodate the main gear. As a first guess non-foldable gear struts were assumed. The retraction and accommodation has been selected to be parallel to the fuselage. This enables the gear to “fall down” with the aid of the incoming flow forces and avoids any complex deployment mechanisms. The required gear bay length was estimated to 6 m with a width of 2.5 m. Three load cases have been assumed for initial structural sizing:

- Load case 1: Main gear touch down
- Load case 2: Subsonic manoeuvre with 2.5g normal acceleration and deflection of the outer flap
- Load case 3: Hypersonic manoeuvre with 2.5g normal acceleration and deflection of the outer flap

For vehicle trimming a worst case scenario has been assumed with a failure of the inner flap, which requires a comparatively high emergency deflection angle of the outer flap and generates higher bending moments in the wing structure. The flap structural layout itself has not been part of the wing structure investigations. Instead, the calculated flap area is simply subtracted from the wing planform while the flap forces and moments will be introduced as external loads. The maximum flap loads along the trajectory have been computed and, for convenience, used for both manoeuvre load cases.
Aluminium has been selected as the structural material for the complete wing within the complete PATRAN and NASTRAN modelling and optimization procedure. All wing spars have been clamped at the root. The thicknesses of the structural members have been optimized to receive “fully stressed” design, whereas “Von Mises” stress has been selected as optimization criterion. To reduce the number of design variables, several skin panels as well as rib/spar webs have been merged to form regions of constant thickness. Minimum wall thicknesses have been set to account for manufacturing issues. A fixed relationship has been established between the thickness of the smeared stringer layer and the thickness of the skin. Excessive plate bending and buckling has initially been addressed by manually adapting wall thicknesses in critical regions after the optimization process.
Consequently, an initial guess for the TPS thicknesses had been made. These thicknesses have been subtracted from the wing structure construction height. More recent and detailed TPS investigations will be considered in the next iteration step and may lead to an increase of wing structural mass.

3.2.2 Wing Structural Analysis Results

The left image of Figure 10 shows the structural deformations for the touch-down case, the right one for the hypersonic manoeuvre case with flap deflection. The impact of the concentrated gear or flap load introduction is clearly visible. However, the maximum deflections are still comparatively small with just a few centimetres.



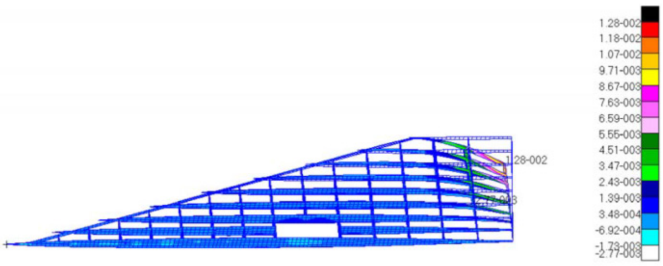


Figure 10: Calculated structural deformations in [m] as caused by main gear touch-down (left), and hypersonic manoeuvre with flap deflection (right)

More detailed results of the calculations, for instance in terms of thickness distributions, can be found in [16]. However the optimization of the wing structure including subsequent manual adaption led to a structural mass for one wing of 8788 kg. Later dynamic analyses for this wing as performed by FOI within the FAST20XX study [16] might result in a further mass increase.

3.2.3 Next Steps for Structural Analysis

As already explained, a reiteration of the wing structure design is required to account for TPS integration. In addition, parametric studies will be performed to further optimize structural arrangement and materials. Nevertheless, the main focus in the future will be placed on fuselage structural analysis. This will also include trade-offs for different rescue stage integration concepts.

3.4. Aerodynamic Shape Design

Preliminary design is generally characterized by numerous shape and system modifications. Therefore complex and time-consuming numerical CFD analyses would not be suitable. For this reason the aerothermodynamic approximation code HOTSOSE (HOT Second Order Shock Expansion method), valid for hypersonic flows and based on Newtonian and additional engineering methods, was implemented at DLR [17],[18].
From the very first idea of SpaceLiner(1) to the development of SpaceLiner6 the aerodynamic design was commonly based on the experience gained from other aerospace configurations and projects with slight variations in dependence on the corresponding HOTSOSE-results. The SpaceLiner7 is the first configuration characterized by an aerodynamic shape arisen from a fully automated optimization process first described in [11],[19] and being continued in [9] and [20]. The optimization loop consists of an analysis module containing HOTSOSE plus mesh generation and the commercial response surface optimization module IOSO NS, both modules coupled via a tool which is capable to manage the interconnection (Figure 11).
In order to consider a wide range of the hypersonic trajectory, three points with different flight Mach numbers and altitudes were chosen for the optimization [11]. As the SpaceLiner volplanes the major part of the trajectory, the glide ratio L/D is the most significant parameter to increase the maximum downrange.
The SL2 and SL4 configurations were taken as the baseline geometries to optimize L/D considering aerothermal loads. A set of geometrical design parameters was released to variegate during the optimization process (nose radius, nose length, wing span, chord length, sweep angle, airfoil thickness) while a couple of geometrical and physical constraints were set (e.g. minimum lift, maximum stagnation point heat flux). The final result of the optimizations, a trade-off between the optima of the three trajectory points, already showed considerable improvements in glide ratio and heat loads and pointed out the clear advantages of a single-delta wing.

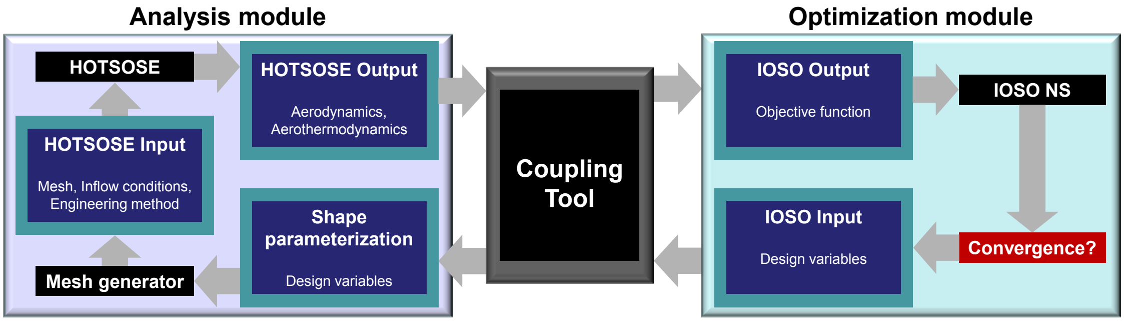


Figure 11: Schematic optimization loop methodology, based on [11]

3.4.1 Recent Design Results

Further detailed optimizations were conducted regarding SL7, taking into account progresses in mesh generation as well as trim aspects which were previously neglected. Also the most recent updates in terms of system requirements were considered. Due to all these updated constraints, 'optimization' in this context cannot mean the consequent improvement of the glide ratio itself but rather the conserving of a sufficient glide ratio under the given conditions.
A general drawback of former analyses was the improper generation of geometry grids using an oversimplified mesh generator which often produced overoptimistic results in HOTSOSE. Thus the improved and more accurate mesh generator GGH (Grid Generator for HOTSOSE) was implemented and included into the optimization loop by DLR-SART. The GGH-mesh of SL7 used as a baseline for further optimization steps is shown in Figure 12.
At the same time more profound analyses in terms of TPS were conducted. Since the extremely high heat fluxes within the spherical nose region necessitate active cooling anyway, the nose radius can now be decreased to a minimum of 0.2 m. To satisfy the need for an efficient TPS at the wing tip, the relative NACA66 airfoil thickness in this region has to be increased from 3.5% to at least 5.5% while the wing tip chord length is set to a fixed value of 11.54 m.

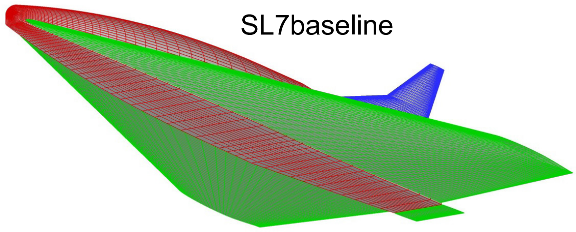


Figure 12: Adapted GGH-mesh geometry of the SpaceLiner7 baseline configuration

An update of the passenger cabin dimensions identified that the fuselage was not sufficiently large to accommodate it. To address this, the cross section of the fuselage had to be enlarged in this region.
Figure 13 shows the results of further shape refinement steps (SL7final), including all the mentioned updates, compared to the results of the SL7baseline configuration. Analogous to the previous investigations, three sample points of the trajectory are chosen.
It has to be noted that the sharper nose in conjunction with the need for an applicable adaption of wing and fuselage as well as the demand for a minimum amount of space for subsystems and the passenger cabin led to an increased nose length of $\Delta l = +3.0$ m.

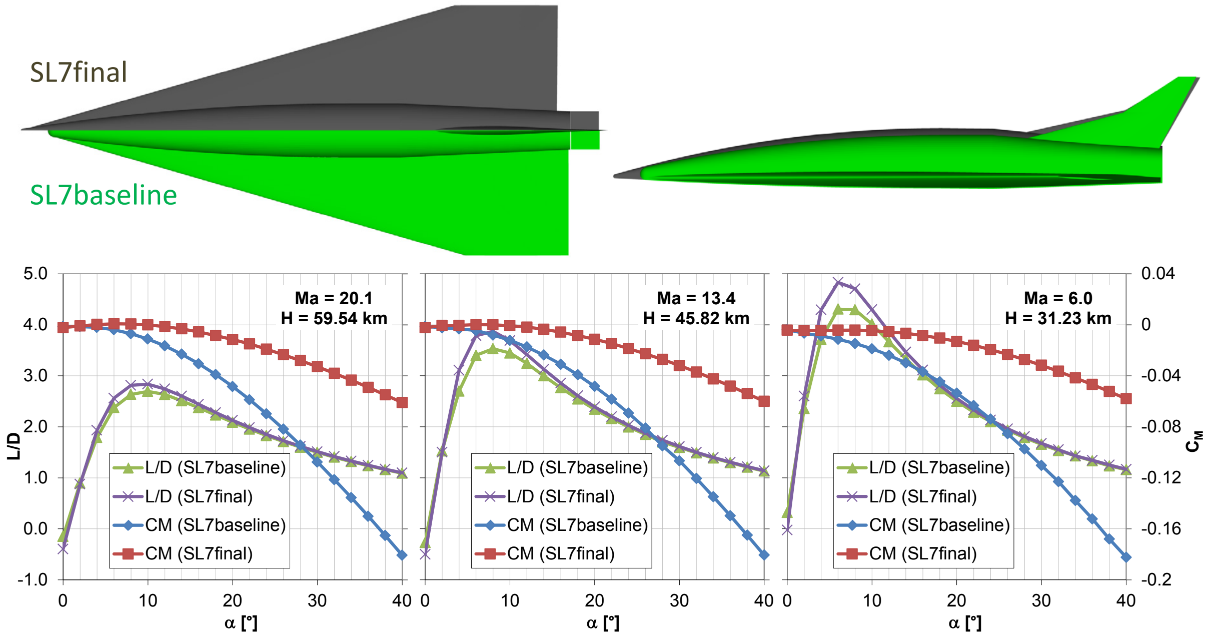


Figure 13: Shapes of SL7baseline (green) and SL7final (grey) and comparison of α-dependent L/D and C_M in three sample trajectory points (A_{ref}=230.5m^2, l_{ref}=63m, x_{ref}=34 m (SL7baseline), x_{ref}=37.286 m (SL7final), turbulent, equilibrium air)

In spite of the more severe constraints, an improvement of glide ratio is achieved along the full hypersonic part of the trajectory. The absolute value of the pitching momentum coefficient is decreased which means a reduction of trim drag.

3.4.2 Next Steps for Aerodynamic Analysis

With the next iteration steps, a more detailed mass model of the passenger cabin and the TPS as well as the influence on the total CoG and hence the pitching momentum coefficient will be considered. Also progresses in more detailed Euler- and Navier-Stokes CFD-calculations with the DLR-TAU-Code about SL4 and SL7 are expected to validate the HOTSOSE-results in some sample trajectory points. A windtunnel-model of SL4 is already planned to be realized and tested, while an analogous model of SL7 will follow. The expected results will also be utilized to validate the numerical calculations and to analyse the performance of the latest promising configurations.

4. Conclusion

The conceptual reusable winged spaceplane 'SpaceLiner' for ultra-high-speed intercontinental passenger transport is proposed and investigated by DLR. Employing advanced but not exotic technologies, the two staged RLV could be able to transport about 50 passengers over distances up to 17,000 km in about 90 minutes. Based on previous studies within the preliminary design phase, the concept is subject to constant iterative development.
The previous skipping trajectory is now replaced by the upgraded non-skipping trajectory because of the advances in passenger comfort in terms of g-loads, the decreasing heat loads and the lower TPS mass.
Recent studies concerning the TPS identify possible TPS technologies and materials and give information about the weight and the influence on structural design. A classic spar/rib/skin design is chosen for the wing structure and analysed in terms of critical load cases while further investigations will consider the latest TPS expertise.
Accounting for the latest system requirements, improved optimization processes are conducted and an improvement of glide ratio and trimming is achieved by modifying the aerodynamic shape of the orbiter. Furthermore, detailed CFD analyses as well as wind tunnel models are planned to be realized.
In summary, although the preliminary design is not foreseen to be finalized for quite some time, the current actual version of SL7 is the most detailed and most thoroughly investigated concept to date. Future research has yet to address the shape and exact position of the passenger capsule and the LOX/LH2 tanks within the fuselage, since this decision will influence the total CoG of the craft. In addition the optimum position of the landing gear has to be deduced, with careful consideration given to its dependency and interaction with other components. It is reasonable to expect that these foreseen decisions and system requirement updates will incur continuing dynamic changes to the concept and the aerodynamic SL shape in the future.

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