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ReFEx: Reusability Flight Experiment – Trajectory Design

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Abstract

The DLR project ReFEx aims at flying a trajectory representative for aerodynamically controlled stages. Further objectives are demonstrating maneuverability capabilities and ensuring safety. The ReFEx trajectory is oriented towards flight paths of operational and conceptual winged reentry vehicles represented in a Mach-Altitude map. Reentry trajectories are designed based on iterative solution of three degrees of freedom equations of motion. To analyze the mission performance under perturbed conditions, they are integrated in a six degrees of freedom, closed loop simulation environment. After the experimental phase and prior to touchdown a reduction of impact energy through a flare maneuver is foreseen.

Acronyms

AoA	Angle of Attack
BC	Ballistic Coefficient
BoGC	Begin of Guided Control
CFD	Computational Fluid Dynamics
DoF	Degree of Freedom
EI	Entry Interface
EoE	End of Experiment
FPA	Flight Path Angle
KTR	Koonibba Test Range
RCS	Reaction Control System
ReFEx	Reusability Flight Experiment
RLV	Reusable Launch Vehicle
VTHL	Vertical Take-Off Horizontal Landing
VTVL	Vertical Take-Off Vertical Landing
WPA	Woomera Prohibited Area

Nomenclature

α	-	Angle of attack	[°]
γ	-	Flight path angle	[°]
ϕ	-	Geodetic latitude	[°]
λ	-	Longitude	[°]
D		Drag	[N]
h	-	Altitude	[km]
m	-	Mass	[kg]
L	-	Lift	[N]
Ma	-	Mach number	[-]
q	-	Heat flux	[kW/m²]
t	-	Time	[s]
v	-	Velocity	[m/s]

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1. Introduction

The idea of launch vehicle reusability goes back to the early days of space flight. While the space age began in 1957, launch vehicle reusability has been the subject of preliminary analyses performed during the 1960s within the early phases of the Space Transportation System development. Already back then a reliable, flexible and economically efficient reusable space transportation system was sought. In principle, these goals have not changed to the present day and with Falcon 9 and Falcon Heavy of SpaceX as well as the X37-B of the U.S. Air Force, examples of currently operational, partially reusable vehicles do exist.
The German Aerospace Center (DLR) is investigating and analyzing reusable launch vehicles (RLV) with the objective of identifying suitable and advantageous launch vehicle designs for future European space transportation systems. These investigations include both theoretical systems analyses as well as ground and flight experiments. The focus of the performed investigations is on first stage reusability. Primarily, two approaches for first stage reusability can be distinguished: vertical take-off horizontal landing (VTHL) and vertical take-off vertical landing (VTVL). In case of the latter, the rocket engines are used to decelerate the stage, limit the loads and perform the vertical landing. As opposed to VTVL, VTHL stages are not using rocket propulsion for reentry and landing. They are equipped with a wing, stabilizers and aerodynamic actuators. After separation of the reusable first stage an aerodynamically controlled atmospheric reentry with limited mechanical and thermal loads can be performed. For the exoatmospheric phase a reaction control system (RCS) is used.

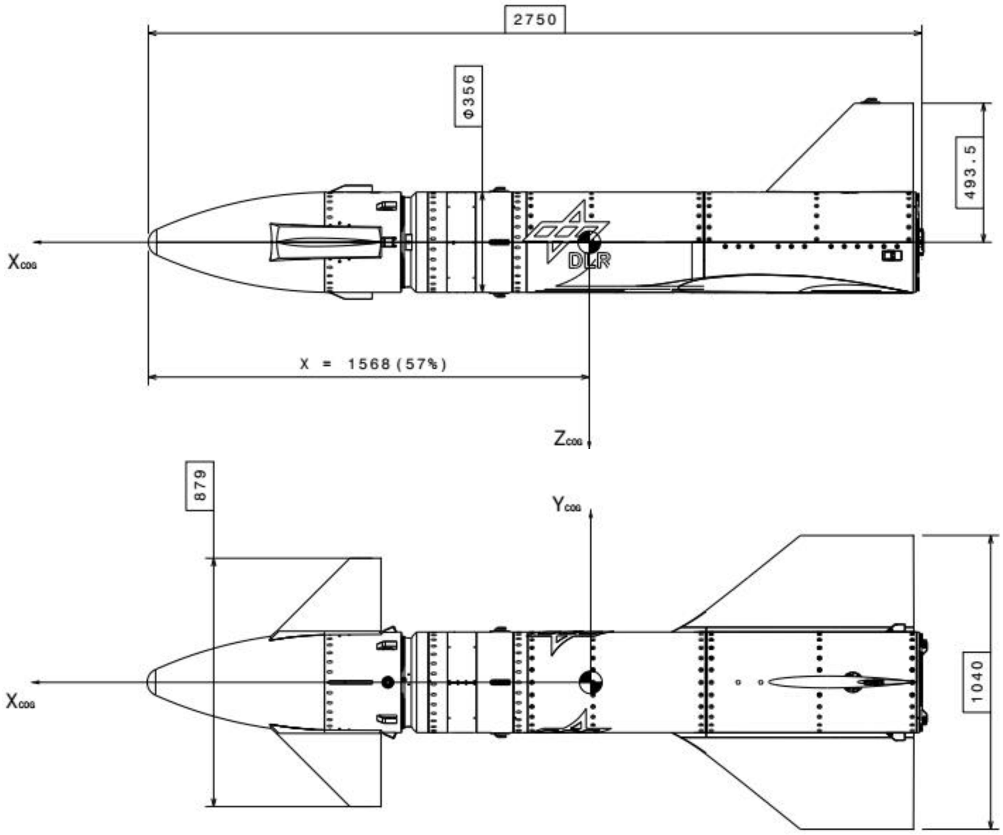

Figure 1: ReFEx principal dimensions

ReFEx as RLV flight experiment orients itself on concepts for VTHL winged, reusable first stages. One of the most detailed investigations in the area of VTHL performed in the past in DLR has been the ASTRA Liquid Fly-Back Booster (LFBB), [1]. In November 2021, the ReFEx project passed the Critical Design Review (CDR) and is currently undergoing final integration and testing at the Institute of Space Systems in Bremen. The approximate dimensions of ReFEx are a length of 2.75 m and a wingspan of 1.04 m. Principal dimensions are shown in Figure 1. The mass of the vehicle is around 400 kg, for more details and an overview over the ReFEx mission see [2], [3] and [4]. A central goal of the Reusability Flight Experiment is the demonstration of controlled hypersonic flight along a reentry trajectory similar to those of full-scale, winged reusable launch vehicles (RLV). Therefore, the ReFEx trajectory is oriented

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towards flight paths of operational and conceptual winged reentry vehicles represented in a Mach-Altitude map. Additional maneuverability requirements are imposed on the ReFEx vehicle and its GNC subsystem. The first being a demonstration of a turn resulting in a significant heading change. Furthermore, a predefined target in terms of position and Mach number is to be reached at the end of the experiment, see [5]. In order to respect all requirements and experiment constraints, reentry trajectories are designed based on iterative solution of 3DoF equations of motion with defined profiles of angle of attack (AoA) and bank angle. An extensive aerodynamic database is used for the determination of areas within the Mach-AoA domain that allow a trimmed flight, see [6] and [7] for more details. The profile of AoA is defined respecting these trimmability areas. The results of the 3DoF analysis represent the nominal ReFEx reentry trajectory. In a next step, the 3DoF nominal reentry trajectory solution is integrated in a 6DoF closed-loop simulation environment, to analyze the mission performance under perturbed conditions.
After End of Experiment (EoE) the ReFEx vehicle will continue with a controlled flight down to an altitude of several hundreds of meters. Prior to touchdown, a reduction of impact energy through a flare maneuver is currently planned. Thus, an analysis of the flare maneuver and its potential to reduce vertical velocity is included in this work.

2. ReFEx Mission Overview and Reentry Trajectory Requirements

2.1. ReFEx Mission Overview

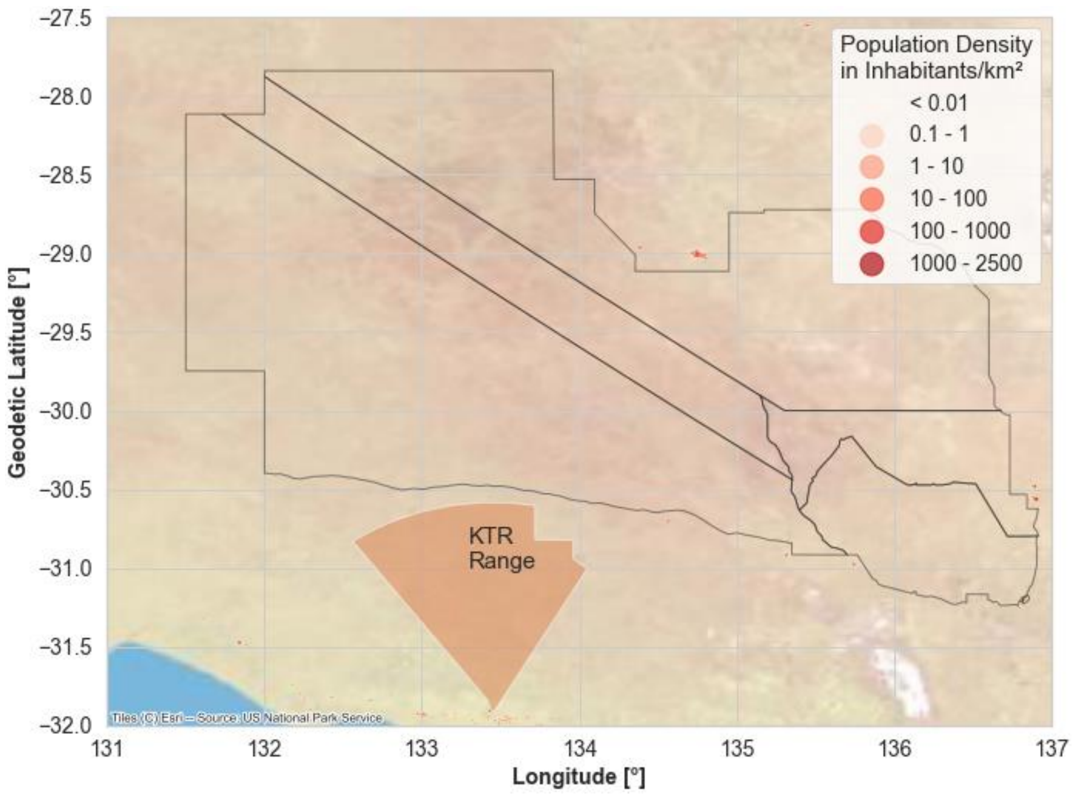

Figure 2: Location of ReFEx flight experiment – Koonibba Test Range and Woomera Prohibited Area

ReFEx will be launched in 2024 from the Koonibba Test Range (KTR) in a sparsely populated area of South Australia. Launching from the KTR, ReFEx will fly in northern direction so that most of the flight experiment will be performed within the boundaries of the Woomera Prohibited Area (WPA). An overview of the KTR and WPA premises together with an indication of population density in this area is shown in Figure 2. A dedicated flight safety analysis is performed to verify and proof compliance with Australian flight safety regulations, see [8] for more details. The overview of the ReFEx mission is shown in Figure 3, [2] and [9]. The mission is separated into two phases: a powered ascent phase where ReFEx is launched on top of a two-stage VSB-30 sounding rocket configuration and an experimental phase which begins after the separation of the ReFEx vehicle from the VSB-30 second stage. During the launch phase the sounding rocket is passively spin stabilized. In contrast to that within the experimental phase the ReFEx vehicle is actively guided and controlled, initially using a cold gas reaction system (RCS) and then transitioning to aerodynamic control once the Entry Interface (EI) in an altitude below 60 km is passed and the dynamic pressure becomes sufficiently high. ReFEx launches with its main wing folded underneath the payload fairing and with inhibited aerodynamic control surfaces. After first stage flight, the first stage is jettisoned and after a brief pause the second stage

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ignites. Upon burnout of the second stage, the vehicle is de-spun using a yo-yo system and the fairing is separated. Following this chain of events ReFEx is separated from the second stage and the main wing is unfolded.

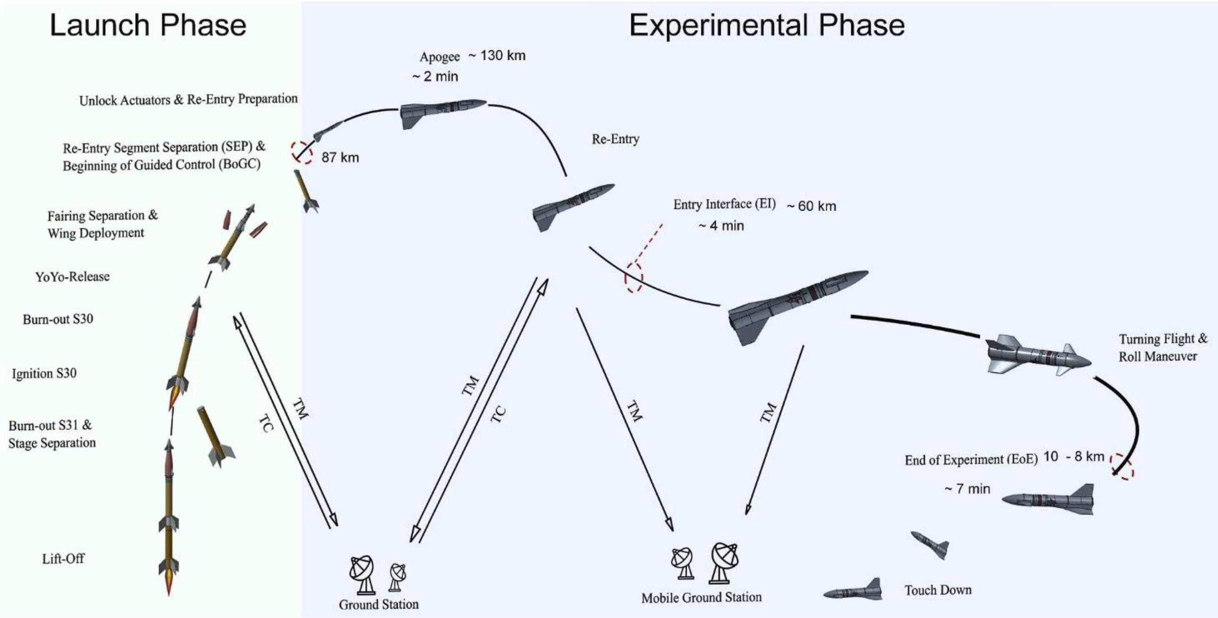

Figure 3: ReFEx mission overview, [2] and [9]

Subsequently, ReFEx begins the experimental phase of flight with guided control (BoGC). As a first step the inhibits on all actuators are removed and the vehicle begins to reorient itself for reentry flight using the RCS, also dissipating any remaining spin left over from the yo-yo deployment. ReFEx reenters the atmosphere in an inverted flight attitude (belly-up) and proceeds to transition from the hypersonic Mach regime to supersonic conditions. At this point a bank reversal maneuver is initiated, returning ReFEx to a belly-down flight orientation, typical for super- and subsonic flight of winged vehicles. In addition to flying the bank reversal maneuver, ReFEx will also demonstrate a turn maneuver, to divert from the current course. ReFEx will continue to transition from supersonic flight, through the transonic regime down to subsonic velocities. The defined guidance target and the End of Experiment (EoE) are reached and ReFEx continues gliding towards the ground while decreasing its velocity. It will approach the ground to within approximately 200 m, with a Mach number of 0.4 to 0.5. Finally, ReFEx will attempt a flare maneuver to reduce vertical velocity and impact the surface.

2.2. ReFEx Reentry Trajectory Requirements

The ReFEx reentry trajectory requirements follow from mission and system requirements, [10] and [11]. The main requirements defined for the reentry trajectory of the ReFEx vehicle can be summarized as follows:

- Reentry trajectory representative of full-scale winged reusable first stages
- Demonstration of maneuverability by performing a significant heading change
- Demonstration of trimmed, aerodynamically controlled hypersonic and supersonic flight reaching a defined target at EoE
- Bank reversal maneuver to be performed at a Mach number of approximately 1.5
- Nominal sideslip angle and rate of 0° and 0°/s

An essential requirement for the ReFEx mission is to fly along a reentry trajectory representative of winged reusable first stages of full-scale space transportation configurations. These first stages separate at hypersonic Mach numbers and begin the atmospheric reentry with a rather high angle of attack that is reduced in the course of the flight. Depending on whether a return to launch site or a down range landing are foreseen a turn and heading change may be performed. Trimmability throughout the entire flight regime is a mandatory requirement for winged reusable first stages. Lateral stability and the ability to control the vehicle attitude dynamics around roll and yaw axes is of special importance. Due to that ReFEx is flying in belly-up configuration in the first part of the reentry and is required to perform a bank reversal maneuver at Mach 1.5.

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3. Reentry Trajectory Design

3.1. Trajectory Design Process

In the following, a description of the ReFEx trajectory design process is given. In the course of the project the ReFEx reentry trajectory went through several iterations. Amongst others, these have been due to changes in geometry, ascent trajectory, aerodynamics and launch site. Also, the trajectory design process itself is an iterative one. Nominal trajectory calculations in 3DoF are followed by calculations in 6DoF that are performed to verify and if necessary refine the defined nominal flight path. The reason to start the trajectory design in 3DoF is its reduced complexity as compared to a 6DoF setup. This is due to the neglection of attitude dynamics, as only the translational dynamics is considered. For the process of ReFEx trajectory design, this means no actuators need to be modelled. Furthermore, a simplified version of the aerodynamic database can be used, in which the aerodynamic coefficients only depend on Mach and AoA. Whereas no guidance and control are performed within the 3DoF analyses, GNC algorithms are part of the 6DoF analysis. This enables to perform MiL (Model in the Loop) analysis of the mission. With respect to the nominal trajectory design, the main objective of this analysis is to verify that the nominal trajectory design is a viable option. This is evaluated with respect to two criteria. First, the vehicle is stable throughout the trajectory. Second, the defined target is reached with the required accuracy, [5]. The ReFEx nominal target state and the corresponding 1-sigma accuracy are given in Table 1.

Table 1: ReFEx nominal target state and accuracy, [5]

	Altitude [km]	Longitude [°]	Latitude [°]	Velocity [km/s]	Mach [-]
Nominal	6.0	132.8	-29.2	0.19	0.6
Accuracy	± 1.0	± 0.07	± 0.07	± 0.05	± 0.15

3.2. Reentry Initial Conditions

Table 2: Nominal ascent final / reentry initial conditions (BoGC)

Altitude [km]	Longitude [°]	Latitude [°]	Velocity [km/s]	FPA [°]	Azimuth [°]
85.1	133.4	-31.3	1.35	43.9	358.5

Launched on a two-stage VSB-30 sounding rocket configuration, the ReFEx vehicle nominally separates from the launcher at conditions shown in Table 2. These final conditions of the current nominal ascent trajectory are an input for reentry trajectory calculations and represent the vehicle state at Begin of Guided Control (BoGC). Separation takes place at an altitude of 85.1 km and a velocity of 1.35 km/s, the flight path angle is 43.9°. The Mach number is 4.87.

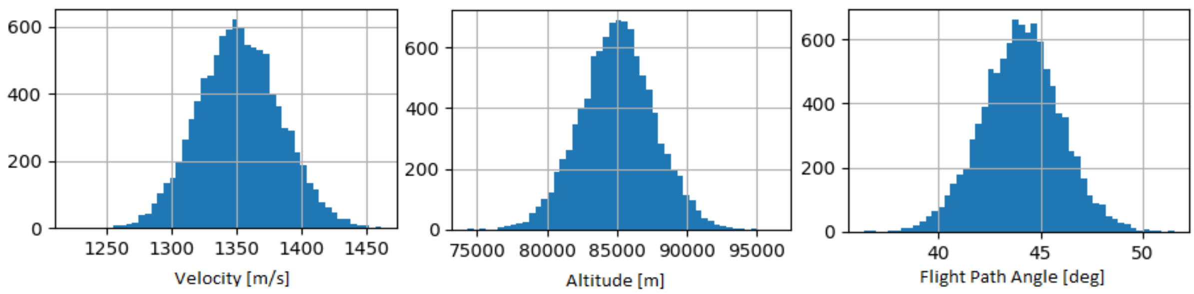

Figure 4: Velocity, altitude and flight path angle dispersion at BoGC for a nominal vehicle mass of 375 kg

It is important to note that conditions at the end of ascent and beginning of descent respectively are subject to dispersions. For instance, the 3-sigma dispersions for altitude, velocity and flight path angle are 8 km, 96 m/s and 5.8° respectively, see Figure 4. Starting from the initial conditions shown in Table 2, the nominal reentry trajectory of

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ReFEx is designed to satisfy the requirements of the flight experiment at the same time respecting all relevant constraints. The nominal ascent and reentry trajectories are calculated for a ReFEx vehicle mass of 375 kg.

3.3. 3DoF Trajectory Simulation Approach and ReFEx Aerodynamics

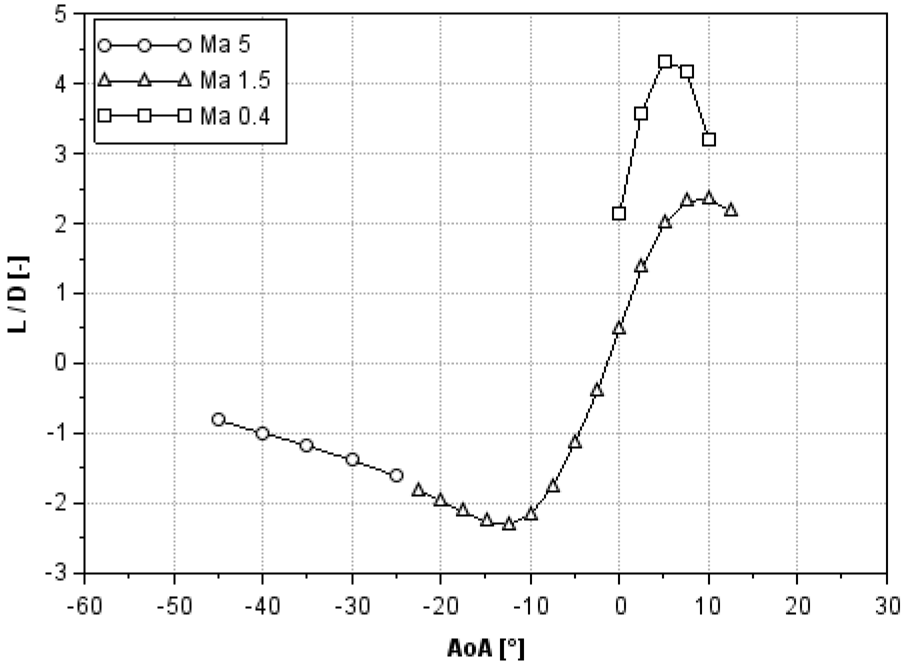

Figure 5: ReFEx aerodynamic database – lift-to-drag ratio for selected Mach numbers, [6]

The trajectories are calculated using the DLR in-house tool TOSCA (Trajectory Optimization and Simulation of Conventional and Advanced Space Transportation Systems), [12]. This tool allows the calculation of ascent and descent trajectories flown by launchers, spacecraft and reentry vehicles through the solution of the equations of motion of a point mass (3DoF). The trajectory control is done via the angle of attack and bank angle, i.e. time histories of AoA and bank angle need to be provided as an input for trajectory calculation. The numerical integration of the equations of motion is performed with a Runge-Kutta-78 method. Different central bodies, as well as atmospheric and gravitational models can be selected. For this work, the WGS84 reference ellipsoid along with a gravity model with four zonal harmonic coefficients are employed. A constant mass of 375 kg is used for the simulation of the ReFEx flight experiment reentry trajectory. The NRLMSISE atmospheric model for a launch at 22nd of June 12:00 is used. In all simulations no wind is considered. The 3DoF trajectory simulations are performed in open loop, without including a guidance and control logic.

Aerodynamic coefficients are required for simulation of the ReFEx vehicle reentry trajectory. The values of the aerodynamic coefficients to be used by the 3DoF trajectory simulation tool are stored in a table as function of angle of attack and Mach number. The aerodynamic coefficients are based on CFD calculations made with the DLR in-house tool TAU, see [6] and [7]. The Mach range from Mach 2 to Mach 5.5 is analyzed by means of inviscid Euler simulations. However, a viscosity correction is applied afterwards to the results of the inviscid CFD calculations. The aerodynamic database for Mach numbers from 0.4 to 1.7 is generated through RANS simulations. The flight vehicle starts reentering the atmosphere in belly-up configuration with a bank angle of more than 180°. To generate lift, negative angles of attack are required. Around Mach 1.5 a bank reversal maneuver is performed and flight continues with bank angles slightly above 0° and positive angles of attack. As a consequence, the aerodynamic database is calculated for negative AoAs, representing belly-up orientation, and positive AoAs for belly-down configuration. Throughout the entire flight regime, the ReFEx vehicle is required to be aerodynamically trimmed. For 3 DoF reentry trajectory simulations, only lift and drag coefficients in a trimmed vehicle state are used. Figure 5 shows the L/D ratio at trimmed flight conditions for Mach numbers of 5, 1.5 and 0.4. Maximum (absolute) lift-to-drag ratio at Ma 5 is around 1.6, increases to 2.4 for Ma 1.5 and reaches 4.3 at Ma 0.4. Aerodynamic coefficients for Ma 5 are calculated for angles of attack in the interval [-45°; -25°], those for Ma 1.5 for an interval of [-22.5°; 12.5°] and data at Ma 0.4 is for angles of attack in the interval [0°; 10°].

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3.4. Nominal Reentry Trajectory – 3DoF Simulations

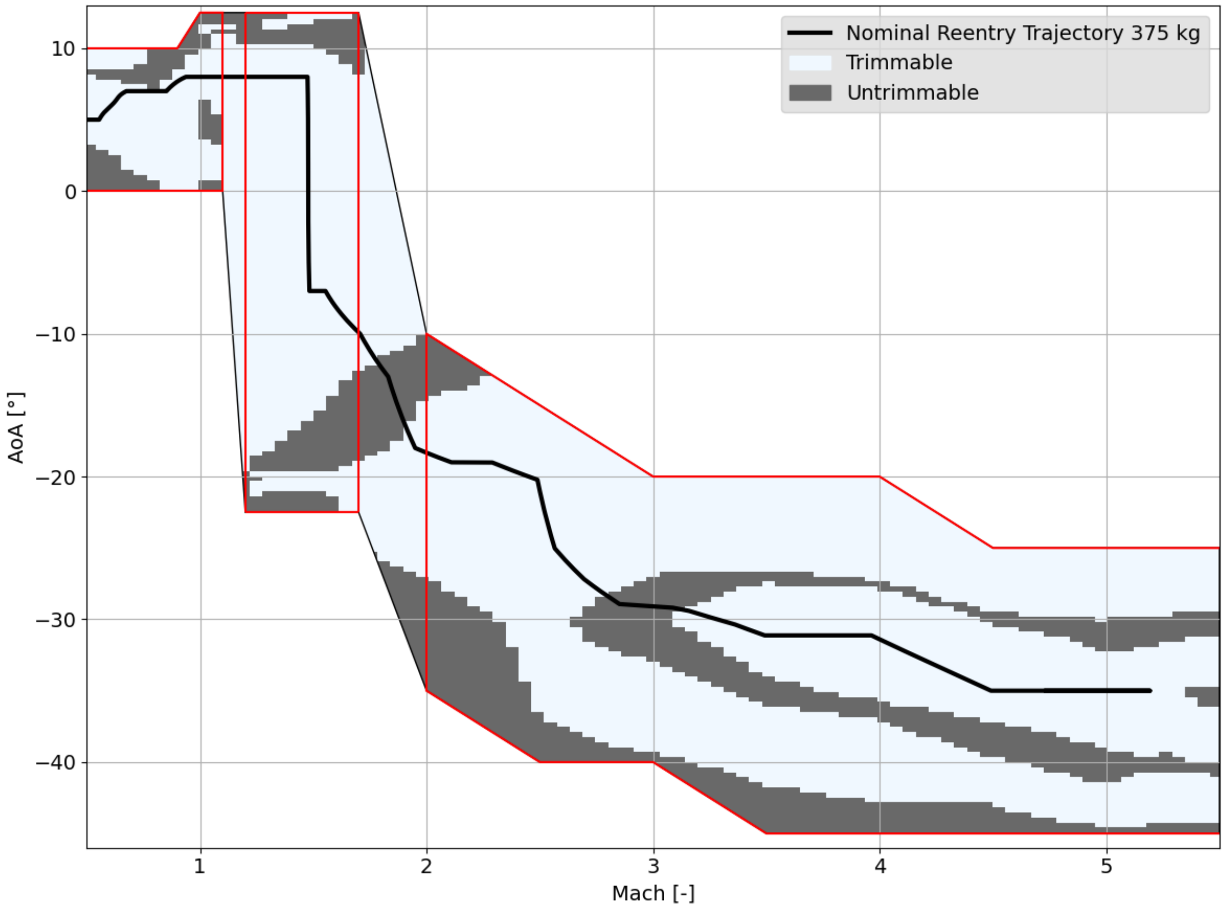

Figure 6: AoA profile for nominal reentry trajectory of ReFEx with a mass of 375 kg

Within the 3 DoF reentry trajectory design process, the definition of an angle of attack profile as function of Mach plays a major role. It shall again be emphasized that for the chosen 3 DoF approach AoA and bank angle profiles are an input to the trajectory simulation program. Along the reentry flight path, it is mandatory to respect the constraint of trimmed flight throughout the entire regime from hypersonic to subsonic Mach numbers as well as the requirement of performing a bank reversal maneuver at Mach 1.5. The nominal trajectory is designed for a sideslip angle and rate of 0° and 0 °/s. This is not achievable in real flight conditions. Consequently, in the process of nominal trajectory definition one has to consider the effect of small non-zero sideslip angles. The planning of the AoA profile includes trimmability constraints related to non-zero sideslip angles through use of an aerodynamic database including moment coefficients of lateral motion.
The angle of attack profile of the current nominal ReFEx reentry trajectory resulting from the iterative 3 DoF design process is shown in Figure 6. The AoA profile of the nominal reentry trajectory for a vehicle mass of 375 kg is shown over Mach in front of regions of indicated aerodynamic trimmability. The regions where trimming is not possible (dark grey in Figure 6) are related to the roll moment behavior of ReFEx in the supersonic Mach regime, see [7] for more details. They are defined based on the number of sideslip angles in the interval of [-2°, 2°] for which it is possible to trim the vehicle. The red boxes in Figure 6 indicate areas for which aerodynamic data from CFD calculations is available, data between the red boxes is extrapolated data. Thus, with every point in the diagram in Figure 6 representing a combination of AoA, Mach and trimmability information, it is possible to respect trimmability constraints related to non-zero sideslip angles and roll moment behavior of ReFEx already during the planning of the nominal AoA profile for 3 DoF reentry trajectory calculations. The nominal reentry profile starts at an AoA of -35° and a Mach number of around 5 in an area of relaxed trimmability constraints. In the following, the magnitude of the angle of attack is reduced step by step. In general, it is attempted to keep sufficient distance to the areas of reduced trimmability and the AoA profile shown in Figure 6 in part is following the borders of the trimmable regions. However, there are two regions of reduced trimmability that have to be crossed when transitioning from the initial conditions at BoGC towards subsonic Mach numbers. The first one being at a Mach number of 3.0 and an AoA of around -30°, the

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second at Mach 1.8 and an AoA of approximately -15°. The bank reversal maneuver is clearly visible as a sharp increase in AoA occurring at Mach 1.5. The angle of attack increases to 8° after changing from the belly-up to the belly-down attitude. Consequently, it is again attempted to maximize distance to the trimmability limits and once in subsonics, the AoA again decreases down to 5°, close to the maximum of the lift-to-drag ratio at Ma 0.4, see Figure 5. Alternative AoA profiles starting at Mach numbers beyond 5.0 and angles of attack below -40° and thus avoiding one of the regions of reduced trimmability are an option and also of interest due to the potential reduction of reentry loads related to the higher initial angle of attack magnitude. However, 6DoF Monte Carlo analysis shows that due to a narrower AoA corridor that needs to be followed in this case along with relatively high navigation errors present at higher Mach numbers, the probability of losing stability during reentry significantly increases. Therefore, this option is currently not considered further.
The resulting nominal reentry trajectory for a vehicle mass of 375 kg is shown in Figure 7. It shows altitude and nose stagnation point heat flux over Mach number. The cold wall nose stagnation point heat flux is calculated for the ReFEx nose radius of 0.05 m with an empirical relationship, [12].

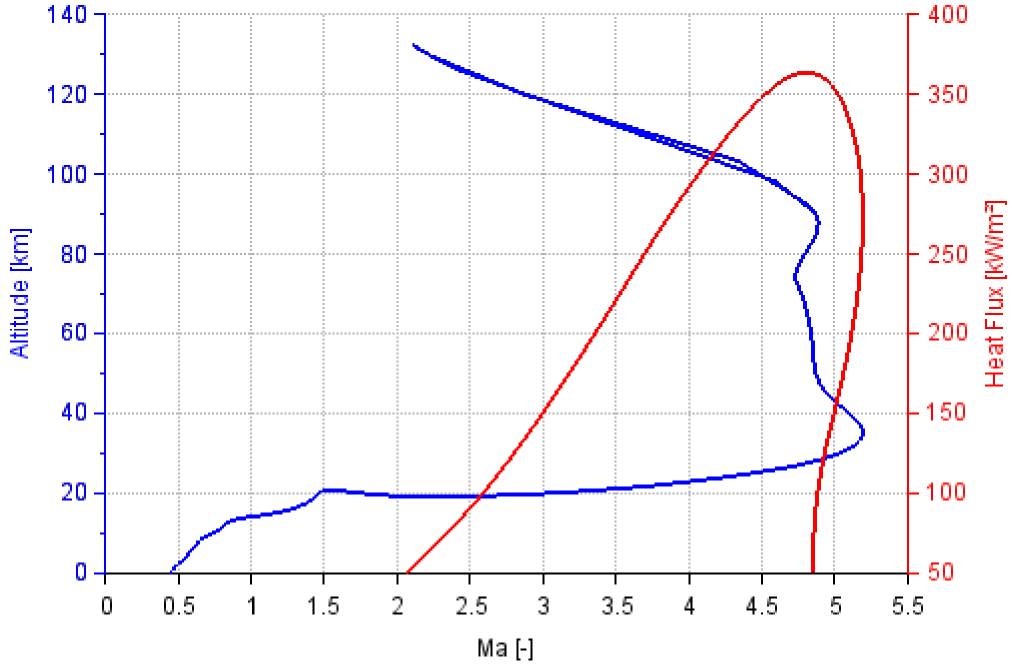

Figure 7: Nominal ReFEx reentry trajectory and nose stagnation point heat flux for a vehicle mass of 375 kg

After separation from the launch vehicle ReFEx is climbing to a maximum altitude of more than 130 km before reentering the atmosphere with a flight path angle of around -44°. The maximum nose stagnation point heat flux of 364 kW/m² is encountered at an altitude of 28 km and a Mach number of 4.8. Maximum dynamic pressure of 41 kPa occurs at an altitude of 22 km and a Mach number of 3.7. The bank reversal is clearly seen as a break in the altitude profile at Mach 1.5. The Mach-Altitude map of the ReFEx reentry trajectory is used to compare the ReFEx flight experiment with concepts of full-scale winged reusable first stages. In this work, the current ReFEx reentry trajectory is compared to a number of conceptual winged reusable first stages analyzed within the DLR internal ENTRAIN study. In this study partially reusable, two-stage-to-orbit transportation systems with different propellant combinations and liquid rocket engine cycles have been assessed, see [13] and [14] for more details. A comparison of reentry trajectories of ReFEx and the ENTRAIN concepts is shown in Figure 8. It becomes obvious, that, after reaching denser layers of the atmosphere, the ReFEx vehicle is entering the Ma-Altitude corridor followed by the selected full-scale RLV concepts. However, there are as well differences that can be observed and two aspects require special attention and discussion. First, in terms of altitude, the ReFEx flight path is rather on the lower limit of a hypothetical reentry corridor. Second, its separation Mach number and the flown Mach number range are smaller than for typical full-scale, winged reusable first stages. The reasons for that are related to the fact that ReFEx is launched on a specific sounding rocket configuration using solid rocket motors and is an experimental vehicle with an internal design drastically different from those of full-scale RLV stages using liquid rocket propulsion.

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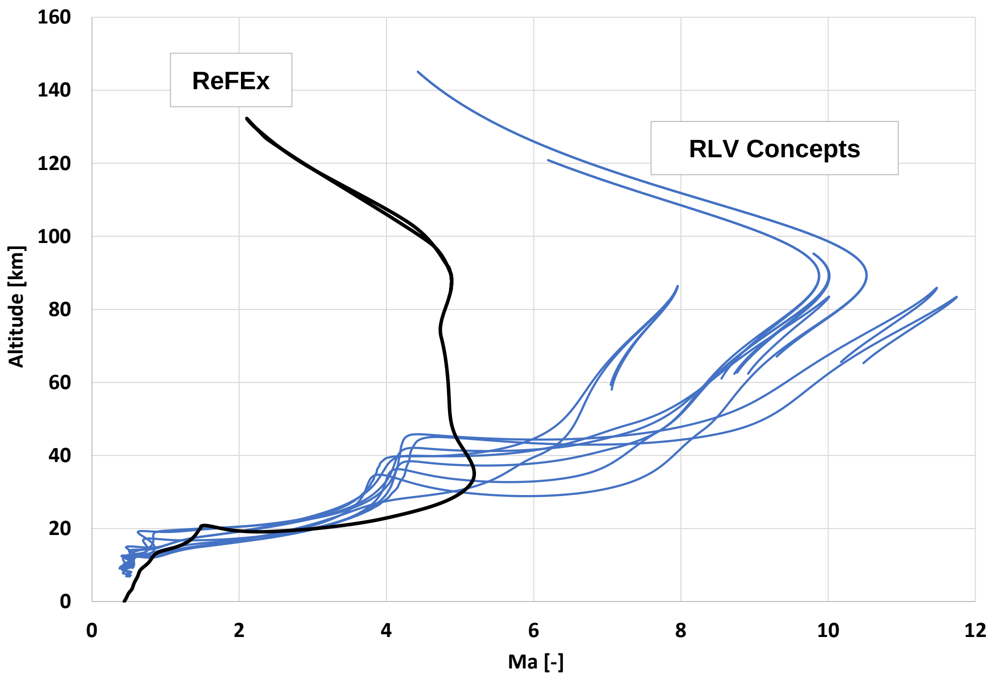

Figure 8: ReFEx trajectory in comparison with full-scale RLV concepts

Due to the constraints related to the ReFEx launch vehicle and the ReFEx vehicle design, the following differences in separation conditions and reentry trajectories as compared to full-scale RLV concepts can be identified. ReFEx does separate at both higher altitude and flight path angle than typical full-scale RLV stages. On the other hand, its separation Mach number is lower while the ballistic coefficient is significantly higher than that of the selected conceptual RLV stages. A comparison of selected trajectory parameters at separation is shown in Table 3. For the RLV concepts shown in Figure 8 minimum and maximum values for the entire selection of full-scale stages are given. The ballistic coefficient is calculated at separation and at an AoA of 0°. Due to its specific separation conditions, the ReFEx vehicle is entering the atmosphere at a higher absolute flight path angle and is encountering deceleration at lower altitudes, see Figure 8.

Table 3: Comparison of trajectory and ballistic coefficient at separation

	Altitude [km]	**Mach [-]**	**FPA [°]**	**BC [kg/m²]**
RLV Concepts Min.	58.0	7.1	8.9	2200
RLV Concepts Max.	67.1	10.5	22.9	3400
ReFEx	85.1	4.9	43.9	7950

3.5. 6DoF Closed Loop Simulations

6DoF simulations incorporate uncertainty models of the vehicle, sensors, actuators and environment, as well as the actual guidance, navigation and control algorithms. The stability and trimmability of the vehicle are of utmost importance. This is a challenge for the ReFEx mission and is strongly affected by the nominal trajectory that is included in the GNC loop. The main driver of this challenge is the particular aerodynamic properties of ReFEx, combined with navigation, control and modelling errors. For example, the angle of attack uncertainty can be as high as 1°, once the vehicle has entered the atmosphere and the dynamic pressure is higher than 1 kPa – outside of that region it is even higher. The attitude of ReFEx is controlled using a set of aerodynamic actuators that includes one rudder and two canards. This design intends to provide attitude control in roll, pitch and yaw. However, due to the effect of the canards flow on the wings, the effectiveness of the asymmetric deflection of the canards may be close to zero for some Mach-AoA combinations and the roll moment coefficient may have a sign reversal. A more extensive analysis of this

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aspect can be found in [7]. Its effect on the controllability of the vehicle is detailed out in [15]. Therefore, it is not possible to fully control the attitude of the vehicle in those regions and they need to be, as much as possible, avoided. In the process of trajectory design it became apparent that it is necessary to cross these regions – see discussion in subchapter 3.4 and Figure 6. This is a critical aspect of the trajectory design and to increase the confidence in the nominal reentry trajectory is a central objective of the performed 6DoF simulations. However, apart from keeping the vehicle stable during the flight it is as well required to reach a defined target at EoE with a determined accuracy. As shown in Table 1, the required 1-sigma accuracy for altitude and velocity is 1 km and 50 m/s respectively. In order to reach this accuracy, the trajectory might need to be modified to compensate for the state deviation at separation from the launcher (see Figure 4), the errors in navigation and control and the modelling uncertainties. Further analyses on how these factors affect the trajectory are shown in [16]. An additional requirement for the ReFEx trajectory is the demonstration of maneuverability by performing a significant heading change.

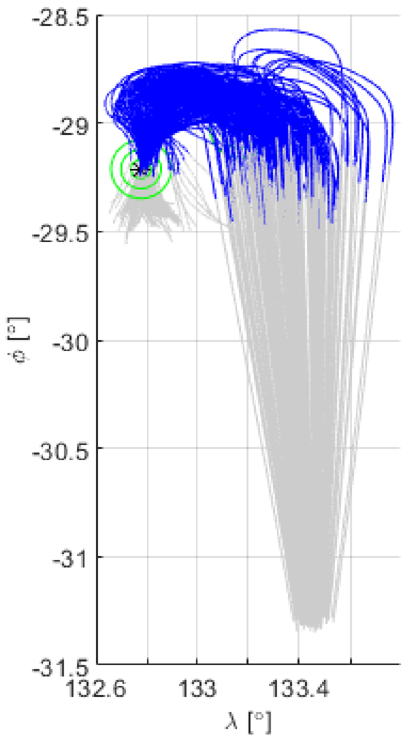

Figure 9: Trajectory from separation to touch-down (blue: between EI/EoE, green: target, grey: prior to EI)

The results presented show a Monte Carlo campaign of 200 runs, in which uncertainties in vehicle, sensors, actuators and environment model are accounted for, and the GNC algorithms are in the loop. Further information on the GNC algorithms is presented in [17]. The simulations start after separation from the launcher. It is important to highlight that there are 5 cases out of the 200 that become unstable throughout the trajectory and are not included in the results. These cases are a consequence of excessive navigation errors and are expected to be solved with the next iteration of the navigation algorithms, without further changes in the nominal trajectory. Figure 9 shows the flown trajectory ground track. ReFEx nominally attempts to fly a left curve from the beginning of its reentry into the atmosphere. When flying north in belly-up orientation the lift vector is turned out of the vertical plane by around 35° (corresponds to a value of 215° for the bank angle). However, major effects on the azimuth occur only at altitudes below 35 km. When decelerating to Mach 1.5, the heading turns towards the west and the bank reversal is performed. The heading change is completed around Mach 0.8 from where the bank angle is successively reduced to 0°. Due to the state uncertainty at separation of the ReFEx vehicle arising from the use of an unguided rocket during the ascent phase, it is not feasible to reach the nominal target from all states within the separation envelope and an alternative target needs to be defined. The nominal target is shown in green in Figure 9. The trajectories are in grey until a dynamic pressure of 1 kPa is reached, as before the aerodynamic loads are considerable small and the trajectory is close to ballistic. It can be seen that despite of a big dispersion in the state at separation the targets are reached with the required accuracy. The necessary modification of the AoA profile in order to reach the targets is shown in Figure 10. Results of the 6DoF closed loop simulations for the angle of attack (blue curves) are displayed within the AoA-Mach corridor for which aerodynamic data from CFD is available (magenta line). Additionally, the AoA profile of the nominal 3DoF reentry trajectory is shown (red line). When comparing the defined 3DoF profile and the 6DoF results, it is important to note,

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that in the frame of 3DoF simulations the AoA profile is defined as a function of time and is an input to the trajectory simulation. In contrast to that, in case of closed loop 6DoF simulations the AoA profile comes from actuator deflection commanded within the GNC loop and the resulting vehicle attitude change. Furthermore, in case of 6DoF simulations the profile of AoA is expressed as a function of energy instead of time as in the case of the 3DoF planning. This does as well contribute to the differences between 6DoF and 3DoF results that can be observed especially between Mach 3.0 and 1.5. In the area where the bank reversal maneuver occurs, the deviations in Mach and AoA can reach up to 0.2 and more than 10°. Outside of that region the 6DoF results corridor is significantly narrower and the observed difference in AoA goes down to less than 5°. In contrast to the nominal AoA profile, the 6DoF results already contain a flare maneuver after EoE as can be seen for Mach numbers below 0.5 in Figure 10. A motivation and discussion of the flare maneuver is given in chapter 4.

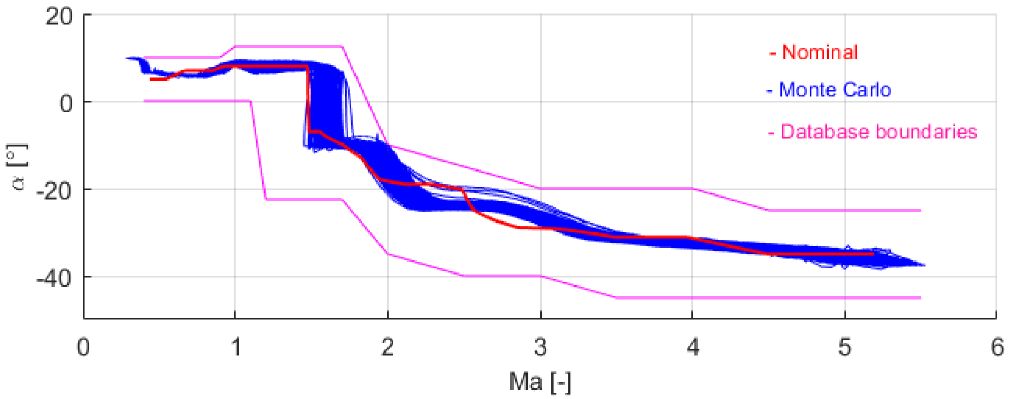

Figure 10: AoA profile – comparison of 6DoF results and nominal trajectory

The Mach-Altitude map of 6DoF reentry trajectory results is shown in Figure 11. The nominal 3DoF reentry trajectory is as well displayed (red line). The altitude covers the range below 50 km after passing the EI whereas the Mach number is between 5.5 and 0.5. At higher altitudes larger differences between the reentry trajectories can be seen. This is mainly due to the relatively high dispersion of the initial conditions at BoGC. At an altitude of 50 km the Mach number varies between 4.5 and 5.3. After entering denser layers of the atmosphere, the cluster of reentry trajectories is less dispersed having a good agreement with the nominal 3DoF profile. Increased differences can again be observed in the area of the bank reversal maneuver.

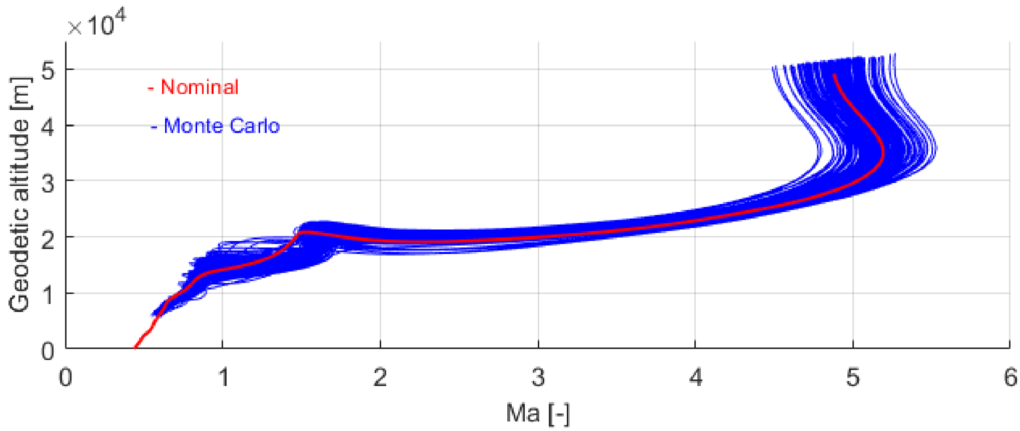

Figure 11: 6DoF reentry trajectory results

The reentry loads encountered by ReFEx are shown in Figure 12. Dynamic pressure and nose stagnation point heat flux are shown as functions of time for the 6DoF Monte Carlo results. Dynamic pressure is not going above 50 kPa whereas the nose stagnation point heat flux (empirically calculated for the ReFEx nose radius of 0.05 m) is surpassing 400 kW/m². Thus, the peak loads observed in 6DoF simulations are approximately 20 % higher than those occurring along the nominal 3DoF trajectory. While a detailed analysis of mechanical and thermal loads for the ReFEx vehicle is not subject of this paper, the occuring maxima are compared with mission requirements that set thresholds on dynamic pressure and nose stagnation point heat flux. The thresholds are marked in red in Figure 12. These requirements have been defined based on Monte Carlo analyses performed at an early project stage with a simplified guidance and control logic. It can be confirmed that the requirements are met with a considerable margin. Finally, it is

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important to highlight that these results show the last iteration of the nominal trajectory and that a considerable amount of intermediate iterations has been performed.

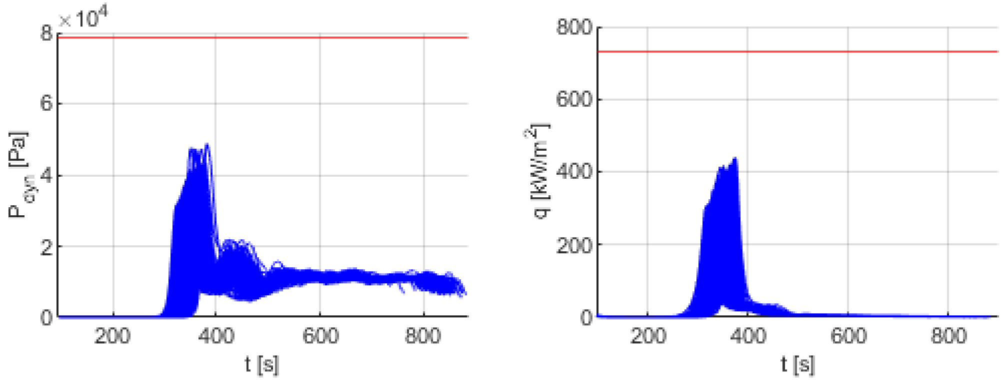

Figure 12: Evolution of dynamic pressure and heat flux

4. Flare Maneuver Analysis

The trajectory design process mainly focuses on the trajectory between separation from the launch vehicle and EoE. The EoE is located at an altitude of approximately 6 km and the main mission requirements are fulfilled after reaching it. However, due to the existence of an on-board memory unit that has to be recovered, there is the incentive to lower the vertical impact velocity while keeping an angle of sideslip close to zero and minimizing the flight path angle for touch-down. Thus, for the post EoE phase an analysis and estimation of ReFEx impact velocities as well as their potential reduction through a flare maneuver shortly before impact is performed. A first assessment is done by performing 3DoF simulations. The starting point of this analysis is the trimmed, subsonic flight of ReFEx with a constant angle of attack. If no flare maneuver is performed, the vertical and horizontal impact velocities shown in Figure 13 are achieved. The range of angle of attack for the points shown in Figure 13 is from 5 to 9 deg. For an angle of attack of 9 deg a vertical velocity of less than -31 m/s and a horizontal velocity of 117.5 m/s are reached whereas for 5 deg AoA vertical and horizontal velocities of -31.3 m/s and 148 m/s are obtained respectively. The minimum magnitude of vertical velocity is seen for an AoA of 7 deg. In case of static, unpowered gliding flight, the flight path angle magnitude can be related to the lift-to-drag ratio:

$$|\tan \gamma| \approx D/L \quad (1)$$

Consequently, the resulting minimum vertical velocity of approximately 29 m/s is obtained at an angle of attack close to the maximum lift-to-drag ratio (see Figure 5).

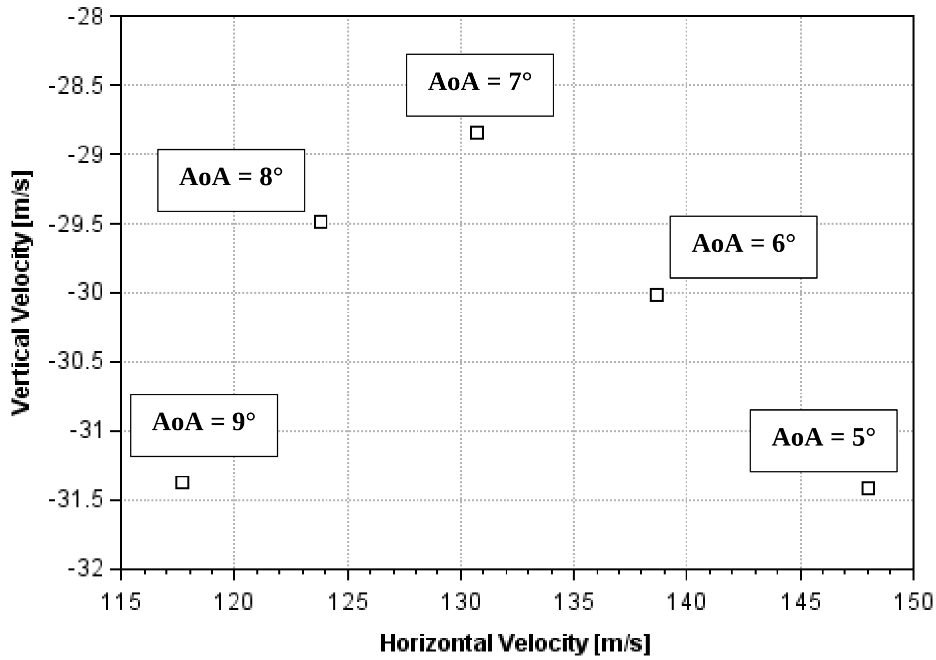

Figure 13: Impact velocity without flare maneuver

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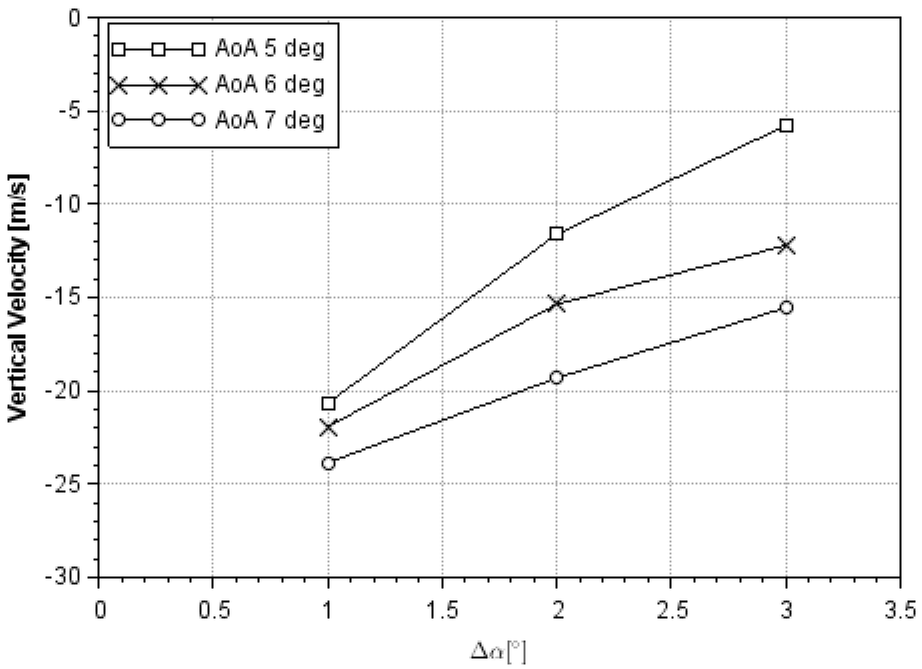

Figure 14: Impact velocity with flare maneuver for different AoA increments

The flare maneuver as analyzed in this work consists of a sharp increase in AoA. This way a further, albeit temporarily, reduction of flight path angle magnitude can be obtained. If the maneuver timing is selected such that impact occurs before the flight path angle magnitude increases again, a touch down with a reduced vertical velocity magnitude is achieved. For unpowered gliding flight without banking the following holds for altitude rate (vertical velocity) and flight path angle rate:

$$\dot{h} = v \sin\gamma \tag{2}$$

$$\dot{\gamma} \approx (v^2/r - g)\cos\gamma/v + L/m\,v \tag{3}$$

The potential flight path angle magnitude and vertical velocity reduction will depend both on the magnitude of the angle of attack increase and the angle of attack before the flare maneuver, since both are related to lift force generation. Results of 3DoF calculations for initial angle of attacks of 5°, 6° and 7° and angle of attack increases of 1°, 2° and 3° are shown in Figure 14. For a delta AoA of 1° the resulting vertical velocities for all initial angles of attack are between -25 m/s and -20 m/s. Whereas for a delta AoA of 3° in case of an initial AoA of 7° the vertical velocity is slightly below -15 m/s. For an initial AoA of 5° it is going up to almost -5 m/s.

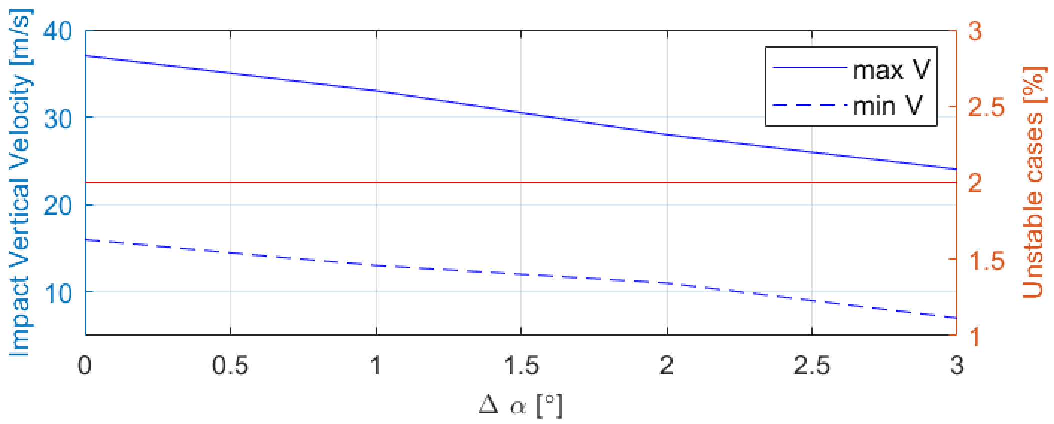

Figure 15: Vertical impact velocity and instability occurrence w.r.t. AoA increases during the flare maneuver

Analogical to the design of the nominal trajectory (see section 3), the 3-DoF analysis is fundamental to understanding the effect of the flare maneuver and to allow rapid analyses. Once the initial design reaches a proper level of maturity, it is tested in 6DoF. The same simulation environment as for testing the overall trajectory was used (see [17]), as the flare maneuver is introduced directly in the guidance algorithms. Within the guidance algorithms the increase in angle

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of attack is fixed and the altitude at which this increase is commanded is the result of an online optimization. This optimization contains a model of the terrain altitude and aims at touching down at the point of minimum vertical velocity. The 6DoF analysis focuses on deciding which increase in the angle of attack to define, which will be a trade-off between the requirement to reduce the impact velocity and the requirement to ensure vehicle stability. A Monte Carlo campaign of 50 runs was performed without a flare maneuver and with flare maneuvers having delta angles of 1° to 5°, see Figure 15. In this figure it can be observed that the impact velocity is considerably reduced by the flare maneuver, without increasing noticeably the appearance of unstable cases up to 3° of angle of attack increase. For higher increases the occurrence of instabilities increases. Therefore, the decision was made to fix this delta at 3°. Figure 16 shows the flight path angle and total velocity at touch-down without flare maneuver. Figure 17 shows the same results with the defined flare maneuver having an AoA increase of 3°. The achieved average decrease in total and vertical velocity is 20 % and 50 % respectively.

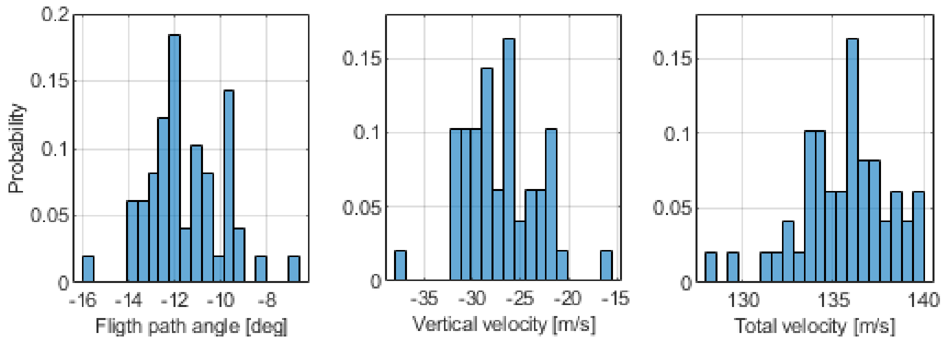

Figure 16: Distribution of velocity and flight path angle at touch down (without flare maneuver)

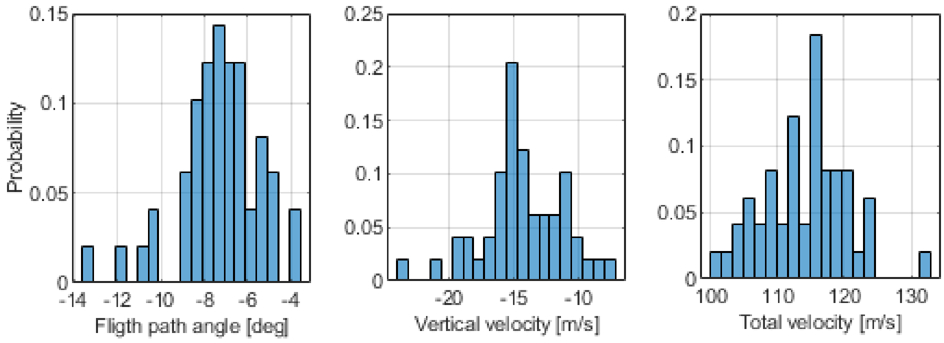

Figure 17: Distribution of velocity and flight path angle at touch down (with flare maneuver)

5. Summary and Conclusions

In this paper an overview on the reentry trajectory design of the ReFEx experimental RLV demonstrator is given. The current nominal reentry trajectory based on 3DoF trajectory simulations is discussed. Furthermore, results of 6DoF simulations showing the influence of initial condition dispersions, control and navigation errors and modelling uncertainties are as well presented. Additionally, a flare maneuver analysis both in 3DoF and 6DoF is given.

Overall the conclusion can be drawn that ReFEx is compliant with all main mission requirements related to its reentry flight path. The performed 3DoF and 6DoF simulations show that an aerodynamically controlled, trimmed flight is possible and requirements for heat flux and dynamic pressure are met with a considerable margin. Despite limitations related to the VSB-30 launch vehicle and its ascent trajectory as well as the design of ReFEx as an experimental demonstrator with a higher ballistic coefficient than typical winged RLV stages, ReFEx does enter the Ma-Altitude region of full-scale winged RLV stages and its reentry trajectory can be regarded as representative for these types of systems. The ability to perform the required bank reversal and heading change maneuvers is as well demonstrated. Furthermore, 3DoF and 6DoF simulations show that a considerable potential to reduce vertical velocity at impact through a flare maneuver does exist.

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