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ENTRY CORRIDOR ANALYSIS FOR VERTICAL LANDING REUSABLE LAUNCH VEHICLES

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ABSTRACT

This work aims at analyzing the impact of the entry burn maneuver on the definition of the trajectory with respect to the atmospheric re-entry performance for a vertical landing Reusable Launch Vehicle (RLV). During the trajectory design phase of a re-entry vehicle, the definition of a feasible space domain, the so-called re-entry corridor, is a crucial point. This analysis defines the flight envelope within which a reference trajectory can be designed to achieve a safe flight until landing while fulfilling aerothermal-mechanical constraints. Aerodynamic solutions are usually adopted, however, for the case of vertical landing RLVs, a retro-propulsion maneuver can be used by means of the engine thrust. In this work, the entry burn is considered and the impact on the flight envelope is explored. To evaluate how this maneuver affects the re-entry trajectory, a tool has been developed. First, the tool computes the re-entry corridor and simulates the trajectory with respect to the parameters that characterize the re-entry burn, such as starting time and duration of the burn. Second, the feasibility of the obtained trajectories is evaluated with respect to the computed re-entry corridor constraints with a parametric analysis. The results show which parameters play a crucial role.

Keywords: Entry Corridor, Entry Burn, Re-entry, RLV

1 INTRODUCTION

During the trajectory design phase of a re-entry vehicle, an important analysis to be performed is the definition of the so-called re-entry corridor. This analysis defines the feasible domain within which a reference trajectory can be designed to achieve a safe flight. For a vehicle returning from orbital conditions, the re-entry corridor is defined by several path constraints. Typically, the entry constraints are the heating rate at the stagnation point, the dynamic pressure, the axial acceleration, and the equilibrium glide condition [1][2]. The re-entry corridor, then, depends on the aerodynamic, thermal and mechanical characteristics of the vehicle itself, which reckon on several design variables and parameters including trim line and entry velocity. Aerodynamics solutions are usually adopted to perform a controlled dissipation of the kinetic and potential energy up to the final desired conditions making use of aerodynamic forces [1][2].

For the case of vertical landing Reusable Launch Vehicles (RLV), some specific features have to be taken into account. These include the possibility of making use of the engine thrust as an additional force for retro-propulsion manoeuvres. An RLV is in fact characterized by low Lift-to-Drag ratio and high ballistic coefficient. As a result, the aerodynamic forces are not enough to slow down the vehicle for most of the cases, even if the initial velocity is suborbital. For this reason, an entry burn manoeuvre shall be performed to reduce the velocity before the aerodynamic phase.

The entry burn manoeuvre depends on several parameters and its design is a key-point for the success of the mission. On one hand, it has to guarantee that the aerothermal-mechanical loads are satisfied both during the manoeuvre and during the aerodynamic phase. On the other hand, however, it has to be taken into account that a retro-propulsion manoeuvre needs additional propellant to be performed, thus affecting the payload capability of the launch vehicle.

To get a better understanding of how the entry burn impacts on the definition of the re-entry trajectory with respect to the entry corridor performance, the equations of the entry corridor constraints are solved, and then, the trajectory is simulated with respect to several parameters which describe the retro-propulsion manoeuvre. At this point, a parametric analysis is carried out and the feasibility of the obtained trajectories is assessed. The analysis aims at identifying how the entry burn manoeuvre affects the trajectory in terms of entry corridor performance, and which parameters have a crucial role for its design.

This analysis will be integrated in a Missionization tool, which is an optimization tool for re-entry vehicles, both lifting bodies and launchers. In this paper, the analysis is limited to the entry corridor performance for the RLV.

2 TOOL AND MAIN ASSUMPTIONS

For the purpose of carrying out the analysis introduced above, a dedicated tool has been developed in MATLAB. The development of the tool embeds some assumptions. The translational dynamics are given by the set of 3DoF equations of motion defined in a non-rotating spherical reference frame. The vehicle is powered and the thrust is included in the equations [1][4]. During the simulation only the entry burn manoeuvre is considered, followed by an unpowered atmospheric phase. The landing burn manoeuvre is not taken into account in this work, and the atmospheric density is modelled with the exponential function. The aerodynamic database, that must be provided as input, is a function of the angle of attack α and the Mach number and is considered trimmed for the whole flight.

The thrust profile is modelled with a trapezoidal function, in order to consider a transient when the engine is switched on and off. The angle of attack profile is instead described with a step function which is kept fixed until the end of the entry burn manoeuvre at a value of 180º, before assuming a user-specified value.

The aerothermal-mechanical constraints, considered for the definition of the re-entry corridor, are the maximum dynamic pressure, the maximum heat flux at the stagnation point computed with the Chapman's equation [1], and the maximum axial acceleration load. The lower bound of the corridor in the velocity-altitude (*V*-*h*) domain is defined by the maximum value among these three constraints. The upper bound is computed by the equilibrium glide condition, or by the terminal velocity constraint if the considered vehicle has a low Lift-to-Drag ratio [1][2][5].

3 ANALYSIS AND STUDY CASE

The first step of the analysis consists on the identification of the parameters that play a crucial role for the design of the re-entry trajectory of a RLV and the definition of the entry burn manoeuvre. In this work, four parameters are considered: the entry burn starting time (tb_{start}), the duration of the entry burn (Δt_{burn}), the thrust level, and the aerodynamic database of the vehicle itself, modified by means of scaling factors. Then, the parametric analysis is performed in order to investigate how the solution changes.

In this work, the Falcon9's BulgarianSat-1 mission is considered as study case [4]. The features of the vehicle are reported in Table 1, and the aerodynamic database (AEDB) is available in [8]. The first step consists of computing the entry corridor performance and then, the identified parameters are tuned in order to obtain the nominal trajectory which was flown during the mission. This procedure is used also to validate the tool. At this point the nominal parameters can be changed one by one and to evaluate how the trajectory is affected in terms of entry corridor performance. The results are reported in Section 4.

Parameter	**Wet mass**	**Reference section**	**Nose radius**	**Max dynamic pressure**	**Max heat flux**	**Max axial load**	**Specific impulse**	**Mass flow rate**
Value	45000 kg	19.4 m^2	1.75 m	1.2 10^5 N/m^2	200 kW/m^2	8 g	300 s	730 kg/s

Table 1: Falcon9 features [6][7]

4 RESULTS

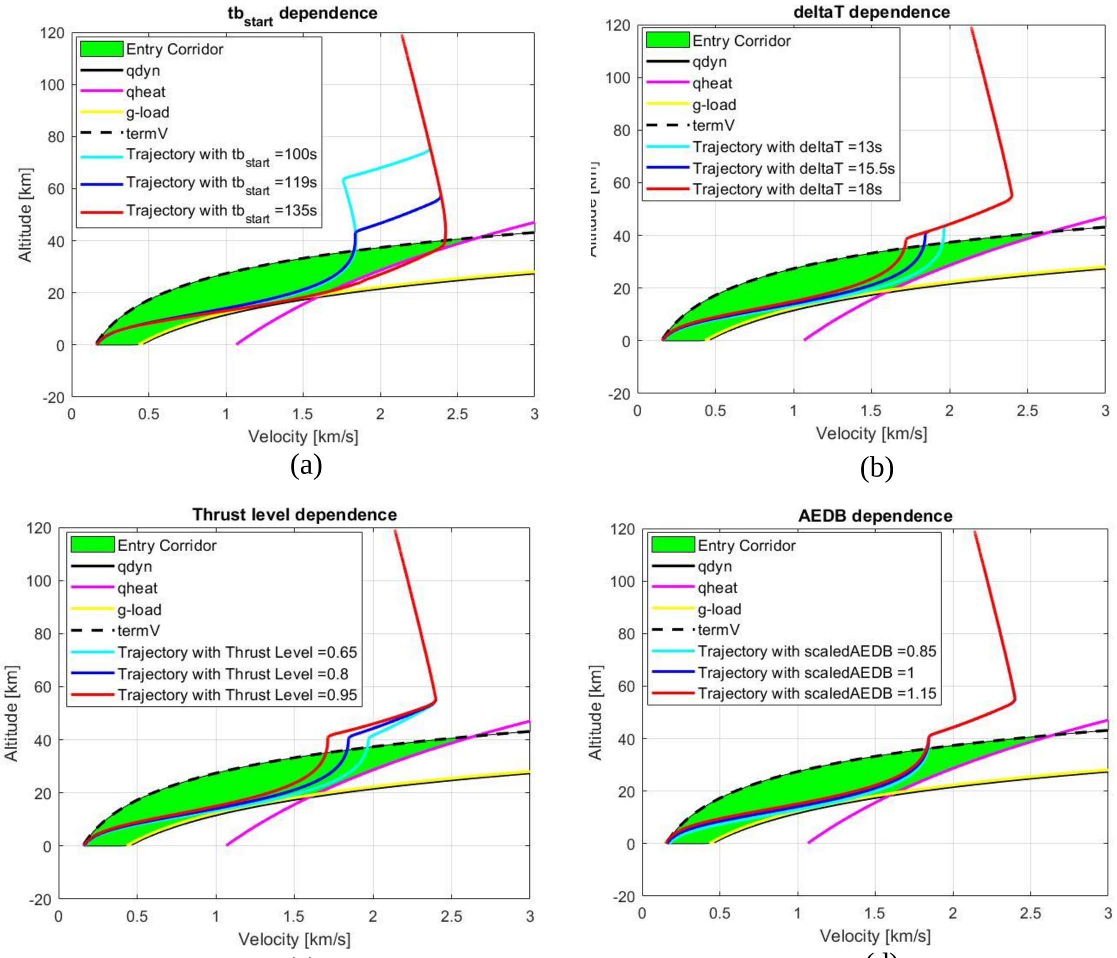
In this section the values of the parameters for the nominal case are given and the parametric analysis is performed.

4.1 Nominal case

A nominal case is set-up in order to properly tune the parameters and reconstruct the selected BulgarianSat-1 reference trajectory of Falcon9. This is the case used to validate the tool. The nominal parameters are 119 s for entry burn starting time, 15.5 s the duration of the burn, 0.8 the level of the thrust, and 1 the scaling factor of the AEDB. The order of magnitude of the errors between the reference trajectory and the simulation are 1 km for the altitude and 10 m/s for the velocity; they are deemed acceptable in this context.

4.2 Parametric analysis

The parametric analysis is performed by varying each parameter one by one, by 15% with respect to the nominal value. The results are reported in Figure 1, and the values of each parameter are given in the legends.



(a) (b)

(c) (d)

Figure 1: parametric analysis: (a) entry burn starting time, (b) time duration of the entry burn, (c) thrust level, and (d) aerodynamic database variation.

The starting time of the entry burn has a fundamental role for the design of the trajectory and the success of the mission. As it is possible to see from Figure 1(a), if the engine is switched on too late, the launch vehicle will encounter unsustainable loads, due to the high velocity in the denser part of the atmosphere.

Even if the entry burn is performed too early, the mission could not be feasible (it is not the case in the Figure), because the vehicle reaccelerates in the upper part of the atmosphere and is subjected to higher loads with respect to the nominal case.

Figure 1(b) shows the impact of the duration of the entry burn manoeuvre. This design variable has a crucial role for the design of the mission. By increasing the duration of the burn, the aerothermal-mechanical loads are decreased. However, in this case more propellant is needed and the payload capabilities of the launcher worsen. If the duration of the manoeuvre is decreased, the vehicle encounters higher loads, as a result of the smaller velocity variation provided, but less propellant is needed. In order to have a feasible and safe trajectory, a trade-off process has to be done depending on which performance to be optimized.

Similar results are obtained also by evaluating different thrust levels, as shown in Figure 1(c). As the time duration of the entry burn, the thrust level is directly linked to the braking capability of the RLV, i.e., the velocity variation that the engine can provide, and so it is connected to the consumption of propellant. However, an important difference with respect to the previous case must be underlined: if the thrust level is too high, the axial acceleration constraint can be violated during the burn. Thus, also in this case, a trade-off process must be considered, taking into account that the upper limit of the thrust level is bounded by both the propellant consumption and the axial acceleration.

Figure 1(d) shows the results when a different aerodynamic database is used. In this case, the drag coefficient (C_D) is augmented by means of a scaling factor to simulate the use of additional drag devices, for example. The AEDB has an important role during the aerodynamic phase of the entry. If the C_D is lower, the vehicle has less braking capability at high altitude, so when the atmosphere becomes denser the encountered loads are higher; the opposite happens for larger C_D. It is worth to mention that exists an interaction between the definition of the entry corridor and the AEDB. By changing the latter, the shape of the entry corridor changes too. However, in this case, the entry corridor performances are kept constant due to the small variation of the AEDB.

5 CONCLUSION AND FUTURE WORK

In this work, the entry burn manoeuvre has been analysed and the key design parameters have been identified. A parametric analysis has been performed to assess how the design of the entry burn impacts the trajectory in terms of entry corridor performance, highlighting also where a trade-off process is needed. The results show that the key parameters must be precisely tuned in order to guarantee a feasible re-entry trajectory.

This work paves the way for the so-called Missionisation process, in which the identified key parameters are optimized to satisfy the customer's mission requirements, and tuned to assess the mission capabilities of a vehicle by defining of common feasible design space domain. The Missionisation tool will consider several analyses, such as Flying Qualities Analysis (FQA), which investigates the possibility of flying the aerodynamic phase with non-zero (or non-180º) angle-of-attack to both generate lift and drag and thus enable trajectory control, but also to increase the drag and relax the propellant consumption.

The future steps are the generalization of the tool and the implementation of a Missionisation layer, which computes and optimizes the values of the identified key parameters while maximising or minimising a given performance.

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