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Optimum Trim of an Experimental Hypersonic Glider

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Abstract

Single point trimming of the hypersonic glider is not sufficient to accomplish the mission requirements and attain maximum performance. Applied to a hypersonic flight experiment, the present research shows that drifts of +/-4% around the centre of gravity imply large penalties on the aerodynamic efficiency along the intended glider trajectory. The analysis is based upon a three degrees of freedom trajectory analysis. Beyond the current parametric analysis, the final manuscript will address the optimization of the vehicle trim to maximize the trajectory performance.

Keywords: *trajectory, trim, optimization*

1. Introduction

A flight test vehicle is being designed to demonstrate various of the critical technologies needed for sustained hypersonic flight [1][2]. The vehicle should realize an autonomous guidance and control to demonstrate to an aerodynamic efficiency in excess of 4 and a hypersonic glide down to Mach 2. The vehicle will be rocket launched to suborbital speed and, once stabilized by the cold gas system, will detach from the service nodule. The vehicle will then be free flying and will initiate a pull up maneuver. During this phase, the trimming of the aircraft is competing between the maneuverability required to carry on the pull up and stability, while at the same time the flight experiment should demonstrate a high aerodynamic performance during the gliding phase.

The focus of the current study is on determining the sensitivity of the trajectory to the location of the aircraft center of gravity (CoG). Whereas the CoG can be established by design, the realization of the vehicle will carry on drifts of the CoG that will be measured and corrected with a ballast mass. Motivated by the encouraging reduction of trim drag by the use of ballast mass reported in [3], the current work shows a preliminary evaluation of the sensitivity of the trajectory performance to the CoG position. Furthermore, an optimization of the vehicle trimming to best fulfill the mission requirements will be presented in the final paper.

2. Methodology

The viscous aerodynamic database of the experimental vehicle comprises the longitudinal and lateral-directional characteristics of the vehicle [4]. For the current purpose, solely the longitudinal coefficients of lift, drag and pitching moment are required. These are considered in the form of three-dimensional tables function of Mach number (Ma), angle-of-attack (AoA) and elevator deflection. For simplicity, the table granularity was reduced to Ma 2, 5, 7 and 9; AoA -6, 0, 6 and 16 degrees and elevator deflections of -20, -15, -10, -5, 0 and 6 degrees. The charts in Fig 2 show the longitudinal coefficients. The vehicle has a reference length (L) of 3.29 m, a span (b) of 1.24 m and a reference planform area of 2.52 m^2. The moment reference centre (MRC) is located at a distance of 57% of the reference length form the nose tip.

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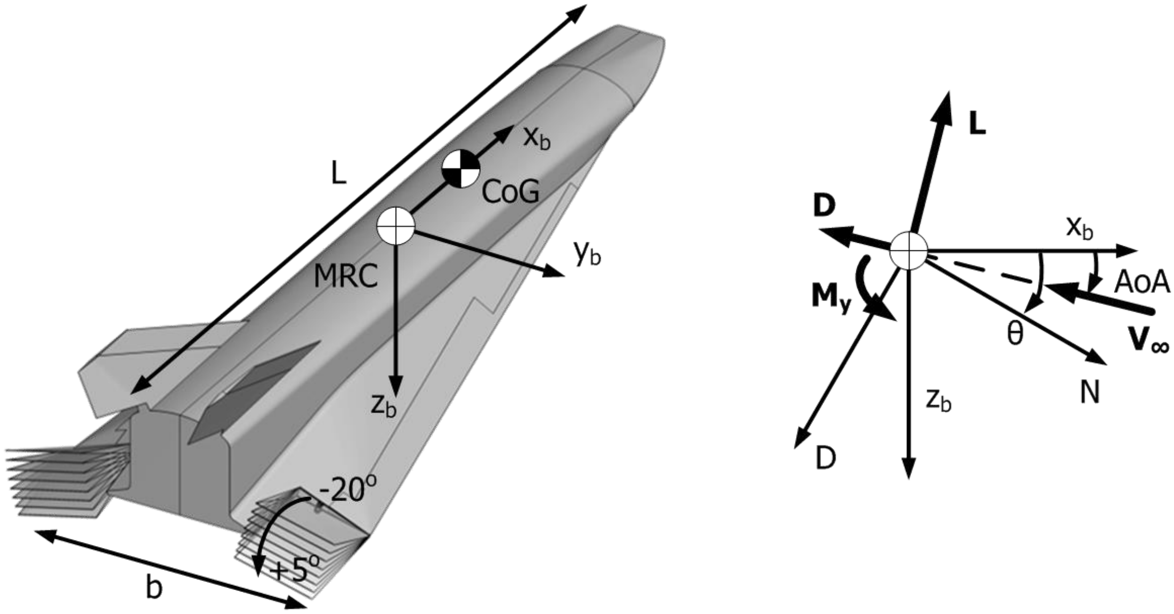

Fig 1. Overview of the EFTV body axes and aerodynamic forces

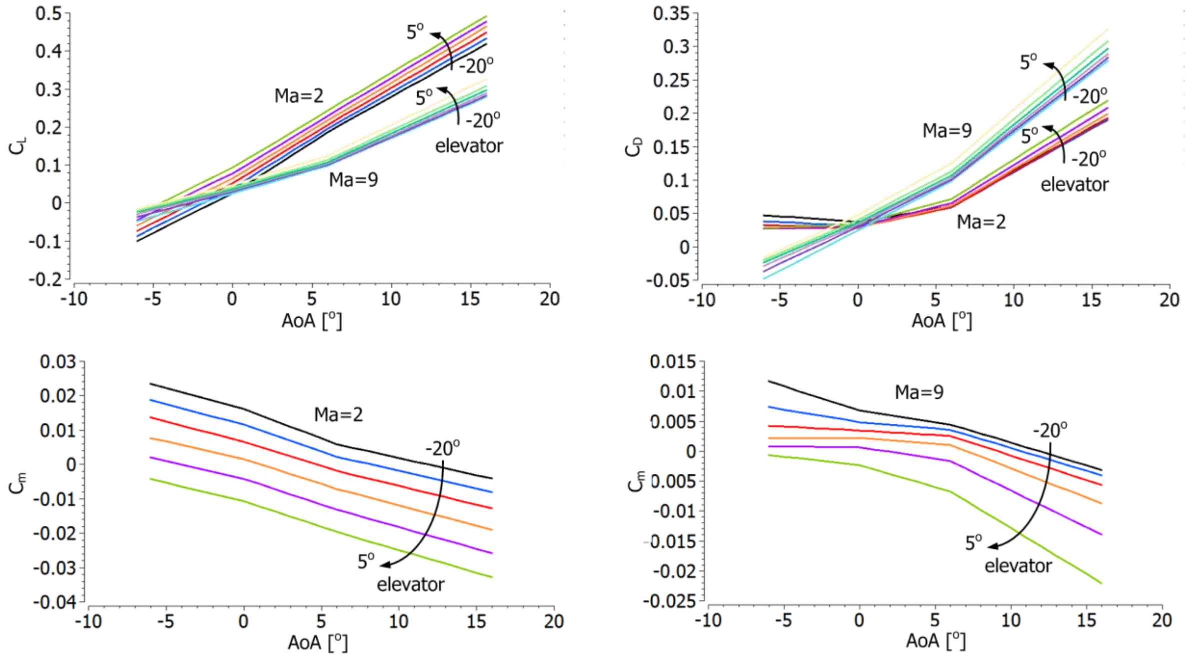

Fig 2. Longitudinal aerodynamic coefficients

The three degrees of freedom model of the aircraft was developed in EcosimPro, by means of the flight simulation library [5]. The pitch rate is set by the pitch autopilot. Default dynamics have been considered for the actuation lane as well as for the dynamic derivatives pertaining to the vehicle aerodynamics. A null pitch rate has been imposed to the trajectories considered herein. The trajectories were optimised by means of the population based stochastic algorithm solver, part of the optimization library of EcosimPro.

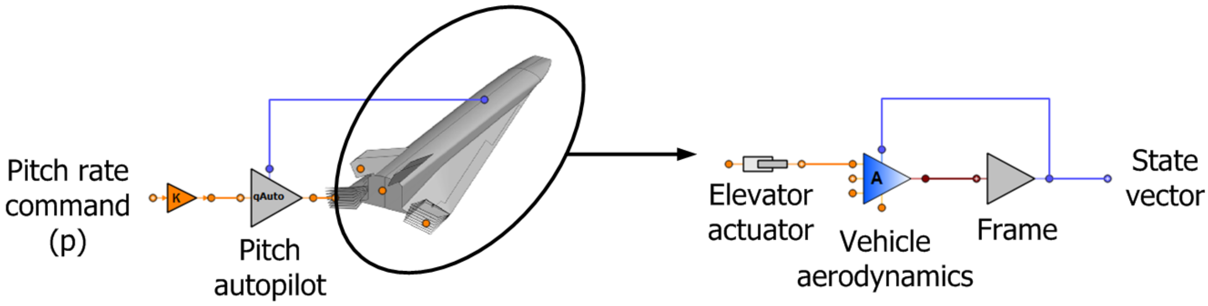

Fig 3. Schematic representation of the aircraft model

3. Results

In the following analysis the vehicle flies at Ma 6.1 and 50 km of altitude with null angle of attack and inclination (θ=0) when the simulation is started. Since levelled flight is not possible with this attitude and flight regime, the vehicle inclination oscillates initially while it evolves towards a steady condition. This can be appreciated during the first seconds on the evolution of the aerodynamic efficiency and elevator deflection, in Fig 4 and Fig 5. The CoG is at 58% from the nose tip. The vehicle mass is 464 kg and the moment of inertia along the Oy_b axis is 1402 kg m^2.

Four simulations were carried out to characterise the trajectory sensitivity to the ballast mass, in Table 1. The CoG shift refers to the position of the CoG with respect to the MRC. The nominal CoG corresponds to the current design target. Both backward and forward deviation of 4% where considered to quantify the sensitivity of the trajectory to the realised CoG positions. Finally, a ballast mass is used to relocate the CoG at the nominal position, at the cost of a 6% increase in aircraft mass. In this case the ballast is located either 5% from the nose tip or 5% from the vehicle base.

Table 1. Trajectory cases

Case	Vehicle mass [kg]	Mass increment [%]	CoG shift [%]
Nominal CoG	464	-	-0.9
Ballast	491	6	-0.9
Backward deviation	464	0	-4.9
Forward deviation	464	0	3.1

The results of Fig 4 show a clear decrease of the aerodynamic efficiency when the CoG drifts forward. The sudden drop takes place just as the vehicle comes out of the pull up manoeuvre, at around 100s into the flight. The reason for this is the increased elevator deflection angle needed to trim the vehicle. The backwards drift reduces the lift-to-drag ratio, nonetheless the trend is not as dramatic as for the forward drift. In fact such trimming is beneficial towards the end of the mission with respect to the nominal case. It can be noticed in Fig 5 that the elevator deflection remains positive throughout the trajectory in the case of backward drift. The ballast trimmed vehicle exhibit the same performances as the nominal CoG case.

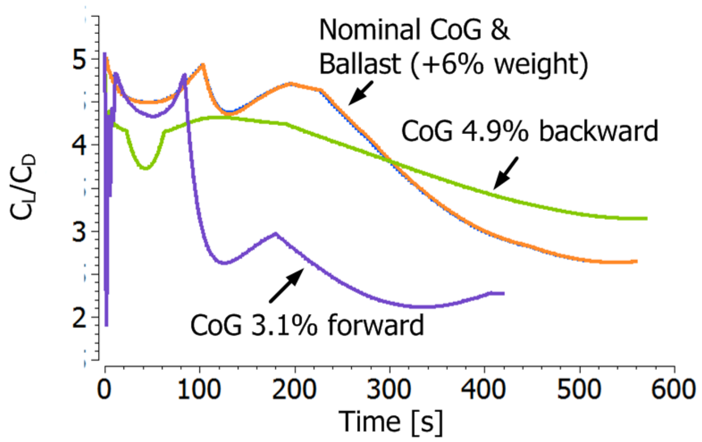

Fig 4. Aerodynamic efficiencies along the four trajectories

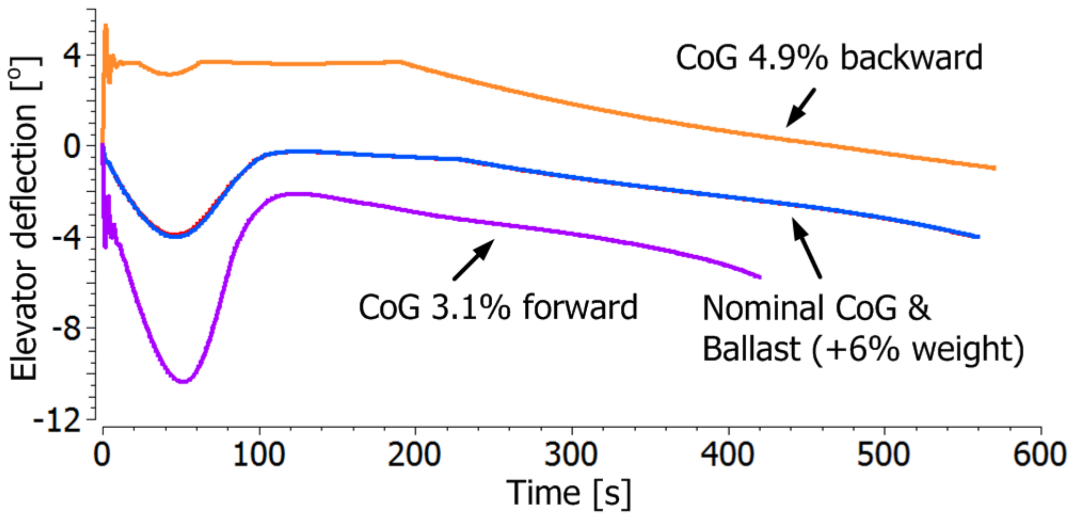

Fig 5. Elevator deflection angle along the four trajectories

Fig 6 and Fig 7 highlight a decrease of 30% and 25% in respectively flight time and downrange due to the CoG forward drift. On the other hand, the ballast trimmed vehicle is able to perform as the nominal one, and the vehicle configuration is clearly more resilient to a backward than a forward CoG drift, performing almost as good as the nominally trimmed vehicle.

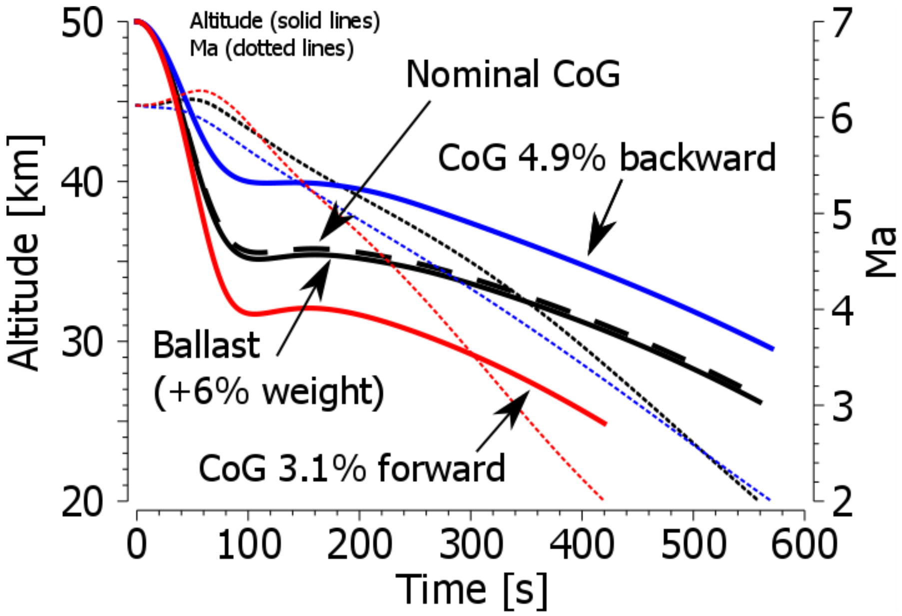

Fig 6. Altitude and Mach number along the four trajectories

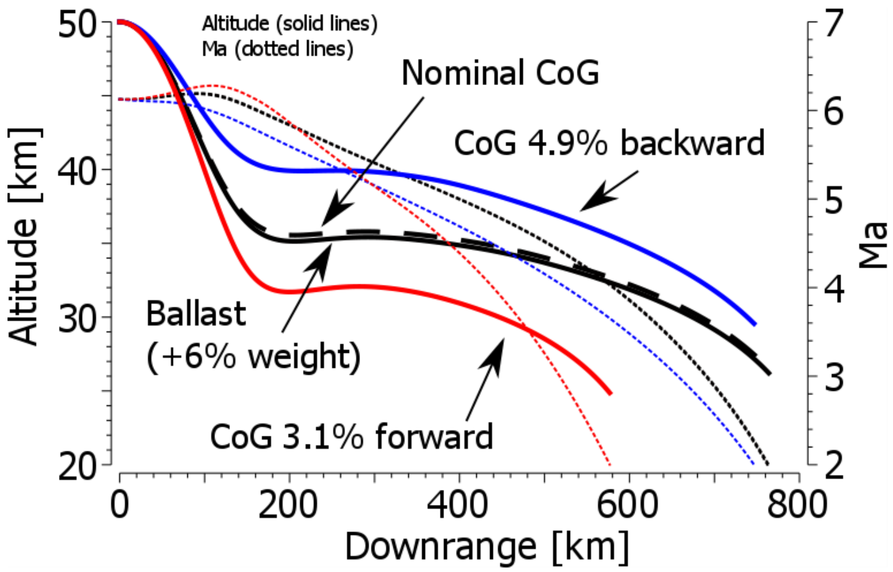

Fig 7. Altitude and Mach number vs. downrange along the four trajectories

In the following trajectory optimisation the current vehicle mass, CoG and trajectory injection conditions are considered:

- Vehicle mass: 400kg
- CoG: 59% from nose tip
- AoA: 3°
- Pitch angle (θ): -18.7°
- Altitude: 55km
- Flight path angle: -21.7°
- Flight path speed: 2334 m/s (V_{xb}=2331m/s, V_{zb}=122m/s)

As optimization variable, the pitch rate command is discretized into 11 control points: the first 7 points at 50 s intervals for a better capture of the pull up maneuver, the remaining 4 follow 100 s time intervals. The optimization objective is to maximize the down range and minimize the pitch angle. For the latter, the RMS of the pitch angle is used with the aim of minimizing the oscillations in altitude after the pull up. Since the method is single-objective, the cost function consist of a weighted sum of both penalties for the minimization problem.

Four optimal trajectories are drawn corresponding to the following CoG displacements: 2% backward, 1% backward, nominal (59% from nose tip) and 1% forward. This is to assess the sensitivity of the trajectory performances to the CoG position.

The down range is little sensitive to the CoG drifts considered, with a variation of 15 km across the CoG positions.

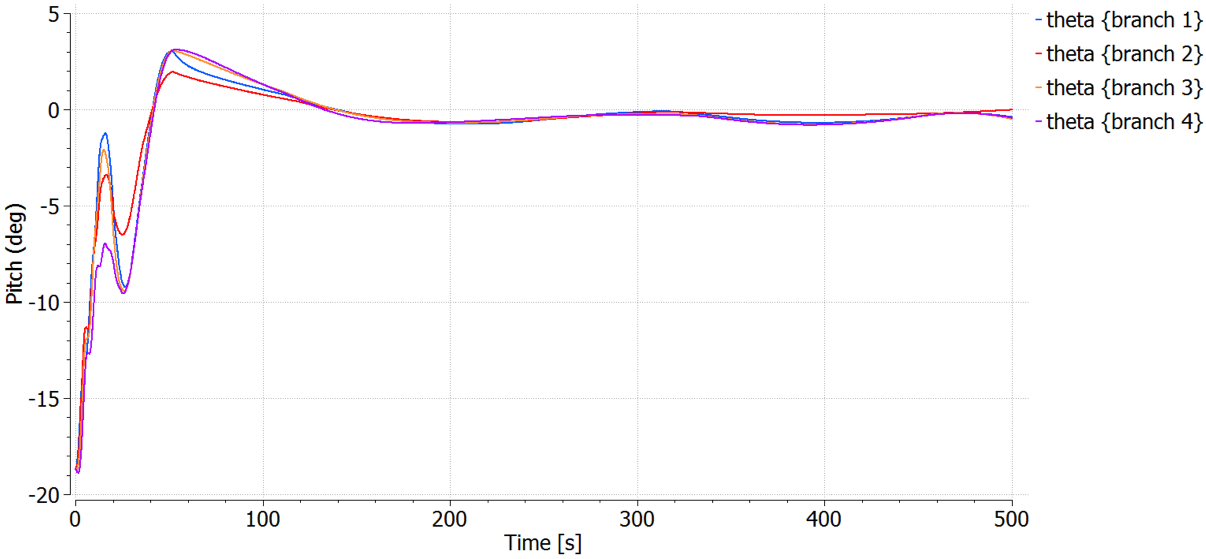

Fig 8. Optimal trajectory pitch angle: branch 1 through 4 correspond to CoG: 2% backward, 1% backward, nominal and 1% forward

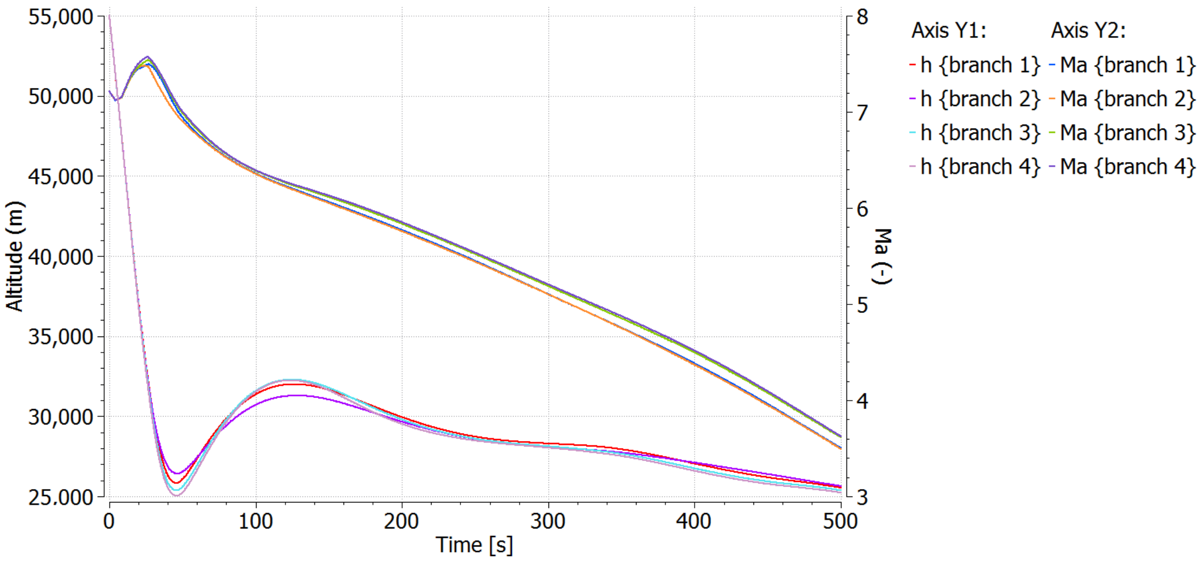

Fig 9. Optimal trajectory altitude and Ma: branch 1 through 4 correspond to CoG: 2% backward, 1% backward, nominal and 1% forward

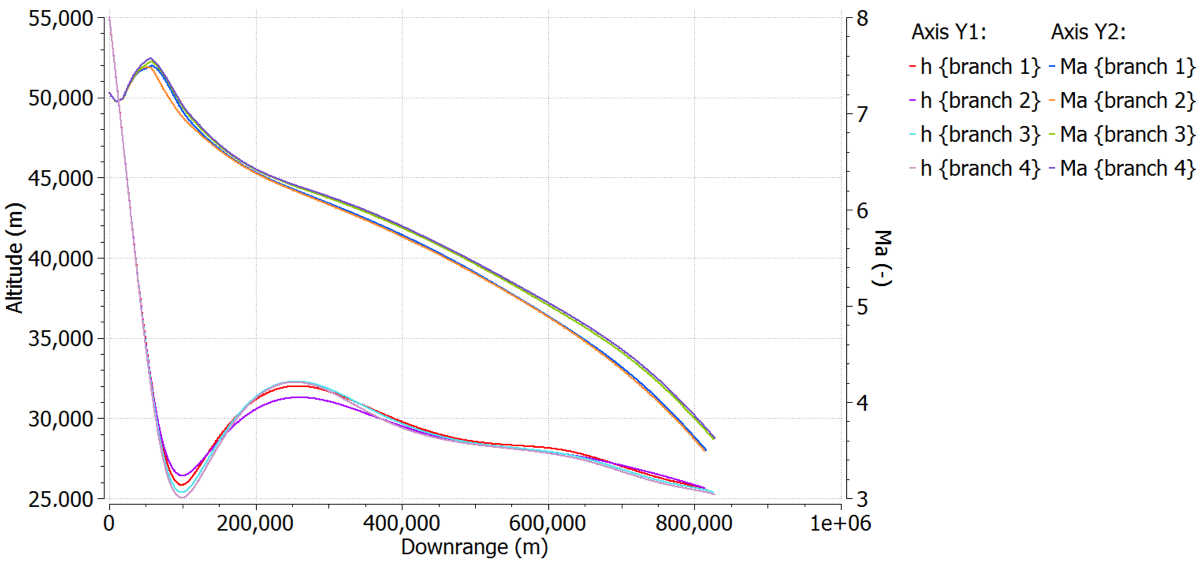

Fig 10. Optimal trajectory altitude and Ma vs. down range: branch 1 through 4 correspond to CoG: 2% backward, 1% backward, nominal and 1% forward

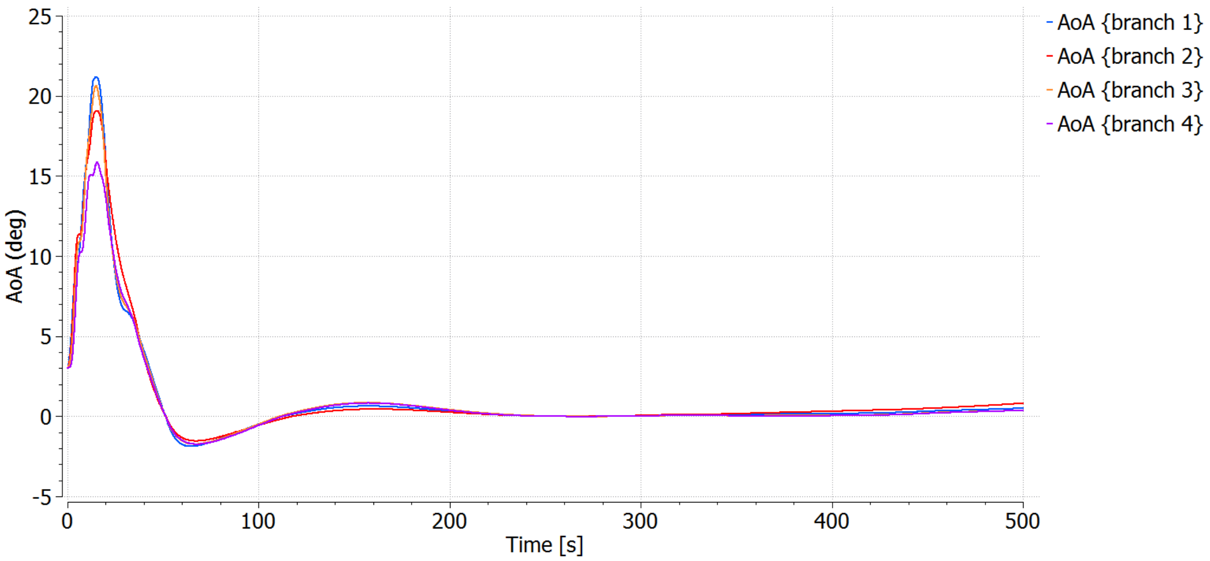

Fig 11. Optimal trajectory AoA: branch 1 through 4 correspond to CoG: 2% backward, 1% backward, nominal and 1% forward

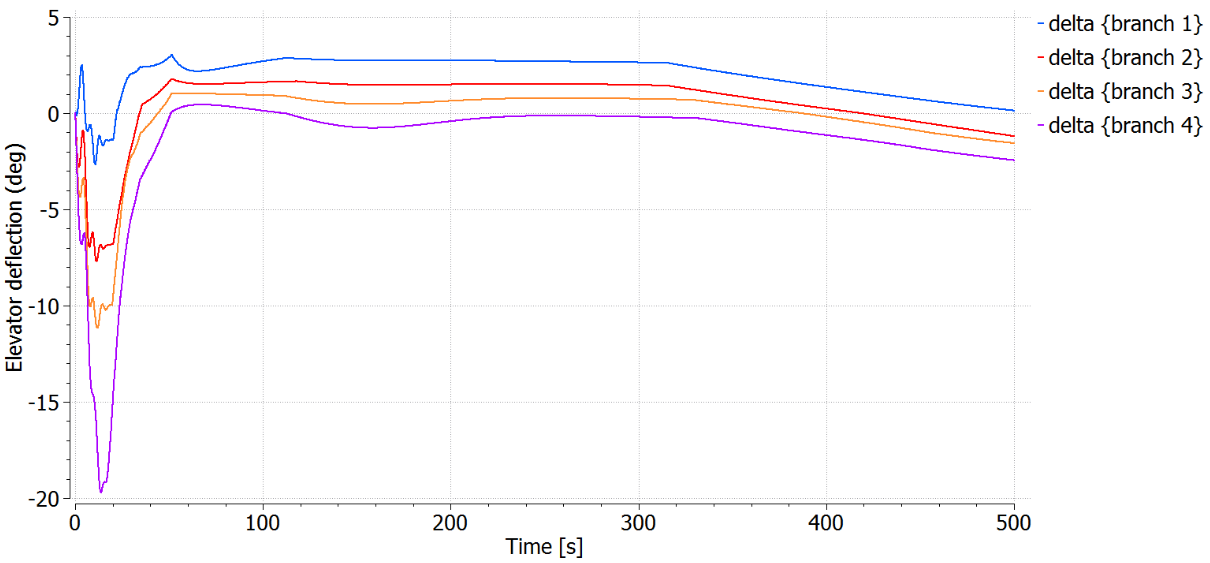

Fig 12. Optimal trajectory elevator deflection: branch 1 through 4 correspond to CoG: 2% backward, 1% backward, nominal and 1% forward

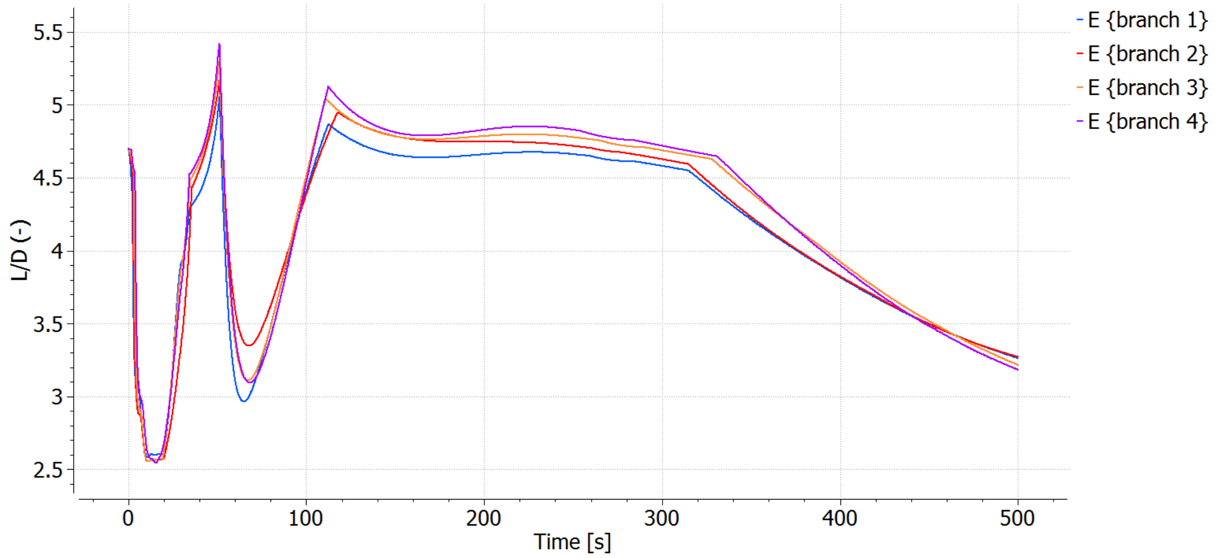

Fig 13. Optimal trajectory L/D: branch 1 through 4 correspond to CoG: 2% backward, 1% backward, nominal and 1% forward

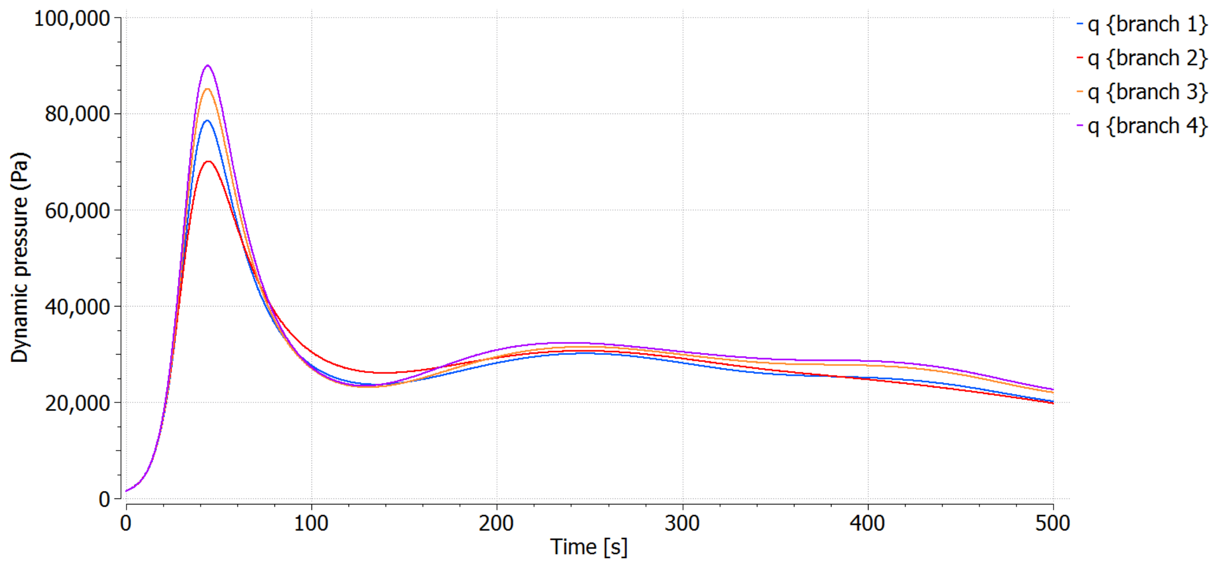

Fig 14. Optimal trajectory dynamic pressure: branch 1 through 4 correspond to CoG: 2% backward, 1% backward, nominal and 1% forward

4. Conclusions

Drifts of +/-4% around the CoG show large penalties on the aerodynamic efficiency along the glider trajectory. Whereas the forward displacement of CoG decreases the aerodynamic efficiency to about 2 and the flight time and downrange to respectively 30% and 25%, the impact of the backward drift is more benign for this particular initial conditions and flight control. The correction of each drift by a ballast mass increases 6% the vehicle mass and brings the trajectories back to the nominal one. The final manuscript will address the optimization of the vehicle trim to maximize the trajectory performance.

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