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NUMERICAL SIMULATIONS OF THE HEXAFLY-INT EXPERIMENTAL VEHICLE

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Abstract.
Hypersonic vehicles have been recently considered as the future of Civil High-Speed transportation. The performance of classically designed high-speed vehicles drop nearly linearly with flight Mach number. Over the last years, however, radical new vehicle concepts were proposed and conceived having a strong potential to alter this trend (LAPCAT-II and HEXAFLY EU-FP7 Projects).
This innovative approach is based upon a well elaborated integration of a highly efficient propulsion unit with a high-lifting vehicle concept. This latter aspect is afforded in the framework of the EU-FP7 HEXAFLY-INTernational Program which foresees the design, the manufacturing and a final flight test of a hypersonic glider. This has to be seen as the only and

ultimate proof to demonstrate the technical feasibility of these new promising high-speed concepts versus their potential in range and cruise.

1 INTRODUCTION

The overall aim of the HEXAFLY-INT project is to design, manufacture and flight-test a high speed gliding vehicle, based on the configuration developed under the previous HEXAFLY project [1][2]. Under HEXAFLY-INT the scramjet propulsion system will not be developed further by the EC-partners, and as a consequence the flight experiment is focused on a self-controlled glider configuration [3].

The prime objectives of this free-flight experiment are:

- a conceptual design demonstrating a high aerodynamic efficiency at cruise with a high volumetric efficiency;
- a positive aerodynamic balance at a controlled cruise Mach numbers around 7;
- a good gliding performance from Mach 7 to 2;
- an optimal use of advanced high-temperature materials and/or structures.

The Experimental Flight Test Vehicle (EFTV) will be launched by a sounding rocket in a suborbital trajectory having an apogee at around 90 km. After the release from launcher, the EFTV performs the early descent flight docked to an Experimental Support Module (ESM). This latter has the aim to control vehicle attitude by means of a cold gas system (CGS) in the outer atmosphere, and by its flare as an aerodynamic mean below about 60km up to 40km. At these altitudes the dynamic pressure does not allow to control the vehicle solely by aerodynamic surfaces. As soon as the EFTV features complete aerodynamic control authority it undocks from ESM and pulls up to perform a hypersonic cruise at about Mach 7. This phase is followed by an experimental window during which the free-flying vehicle (i.e., EFTV) allows demonstrating a high aerodynamic efficiency, a positive aerodynamic balance at controlled cruise Mach numbers and an optimal use of advanced high-temperature materials and structures. So, the appraisal of aerodynamic performance of the EFTV vehicle is mandatory in order to assess the experimental window phase of the descent trajectory, being this phase the core of the mission as we have said above.

In this paper the preliminary aerothermodynamic analysis of hypersonic glider's performances will be done and demonstrated by means of dedicated numerical simulations aimed at the evaluation of global aerodynamic coefficients as well as local wall friction and heat fluxes, being these results the necessary input for the flight mechanics and structural analyses. The uncertainties due to grid refinement and the modelling of turbulence will be faced by means of an accurate sensitivity analyses of main parameters. Preliminary results concerning the nose of the vehicle are shown in the following figure.

2 FLIGHT SCENARIO AND VEHICLE CONFIGURATION

The HEXAFLY-INT mission is conceived to achieve a hypersonic leveled flight at an altitude of about 28-30 km, while being injected from a semi-ballistic trajectory depicted qualitatively in Figure 1, and described below.

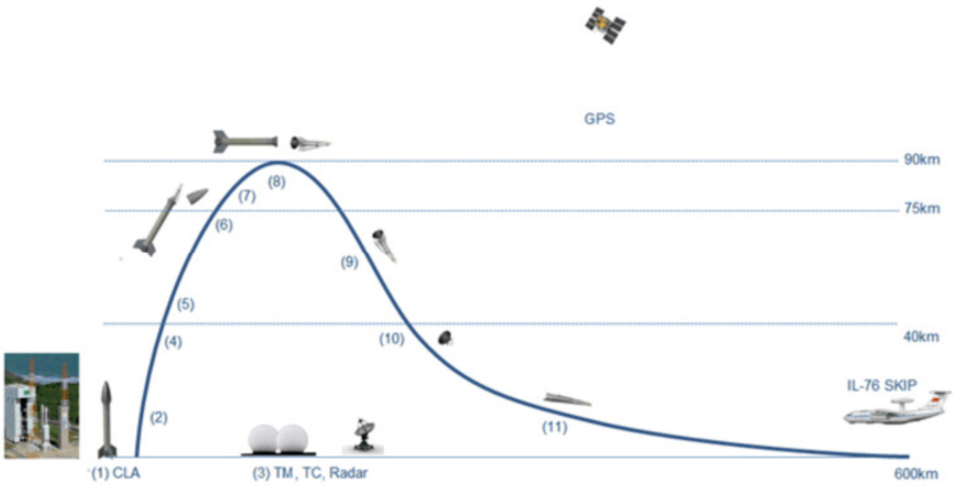

Figure 1 Flight scenario with sequence events

After a boost bringing the scientific payload (EFTV+ESM) to an apogee, it follows a ballistic phase in the outer atmosphere stabilized by an attitude control system in combination with an aerodynamic flare (ESM). The vehicle (EFTV) is detached from the ESM when ESM-EFTV separation conditions are reached. After the separation a pull-out manoeuver brings EFTV to a hypersonic leveled flight at a target altitude of 28-30km [6].

The EFTV + ESM mission shall be constituted by the following phases:

- Pre-launch phase
- Launch phase - Ignition of engine rocket
- Thrust Vector Actuation
- Burn-out of engine rocket
- Ejection of nosecone
- Attitude correction of motor and payload performed by MSM (Motor Service Module)
- Ejection of combined HEXAFLY –INT payload, i.e. experimental vehicle (EFTV) and stabilizing flare (ESM)
- Attitude control with cold gas jets (CGS) in ESM and attitude data from IMU on board of EFTV
- Ejection of stabilizing flare
- Experimental phases I + II (re-entry, pull-out manoeuvre, glide phase from hypersonic to supersonic regime)
- Splash-down.

The vehicle, in the first phase of descent, just after the release from launcher, is composed by the glider, namely EFTV, docked with the ESM, as shown in Figure 2. This configuration allows the CGS thrusters on the ESM to maintain the design attitude during the initial descent into the atmosphere where aerodynamic control is ineffective. Indeed, it is foreseen that the EFTV will separate from the ESM when the dynamic pressure is sufficiently high that the EFTV Flight Control System (FCS) has the necessary control authority and that it can rely purely on aerodynamic control surfaces alone to steer its attitude.

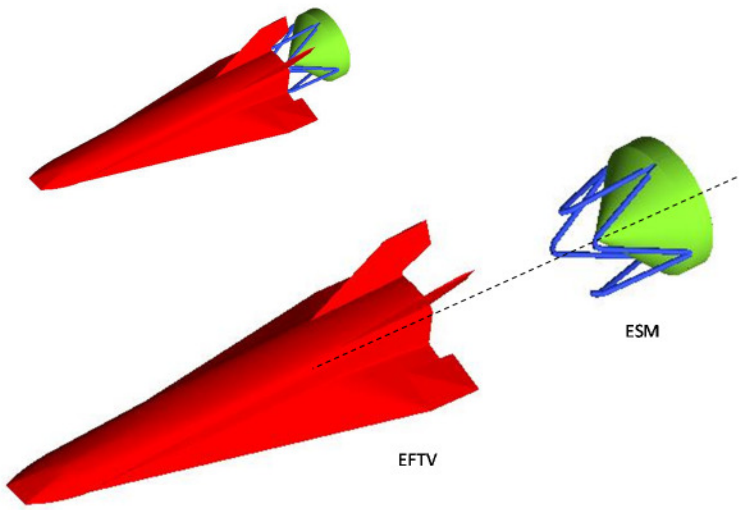

Figure 2 The EFTV+ESM vehicle in docked (top) and undocked configuration (bottom).

Finally, at the separation point along with the descent trajectory, EFTV undocks by ESM to perform the experimental flight.

3 NUMERICAL ANALYSIS

The main aim of the numerical analysis reported in this paper is to find the right methodology to develop a suitable and reliable aero-database to be used as input for flight mechanics and structural analyses. Previous activities gave preliminary results obtained on unstructured CFD grids by using commercial codes. In order to be more confident and to reduce the uncertainties of CFD calculations additional simulations have been foreseen on structured grids and in-house CFD codes. At the moment two main activities started and are providing first results of this second phase: the nose-only calculations and the full vehicle (EFTV) ones.

The flight conditions (far field, body surface and attitude) reported in Table 1 are considered for the present calculations of both nose and full vehicle.

H	30	Km
Mach	7.25	-
p	1208	Pa
T	226	K
AoA	0, 12	Deg
Delta_f	-10, -5, 0, +5	Deg

Table 1: Flight conditions.

3.1 Nose

The nose-only computations have been carried out mainly in order to have an assessment of the codes used (Fluent and the CIRA code), and the influence of the numerical schemes and shock refinement on the quality of final solution. Being the shock fitting not easy to apply to the full vehicle, a comparison of solutions can give us an uncertainty especially for what concerns the nose heat-flux evaluation. Figure 3 reports a qualitative picture of a nose stand-alone simulation. The grid used in composed of about 0.4 million of cells and has first grid cell at wall of about 1 micron (10^{-6} m) all over the surface.

The far-field conditions are representative of a particular point of the hypersonic gliding trajectory (point A: time about 300s, max. AoA, a/g, see Figure 4).

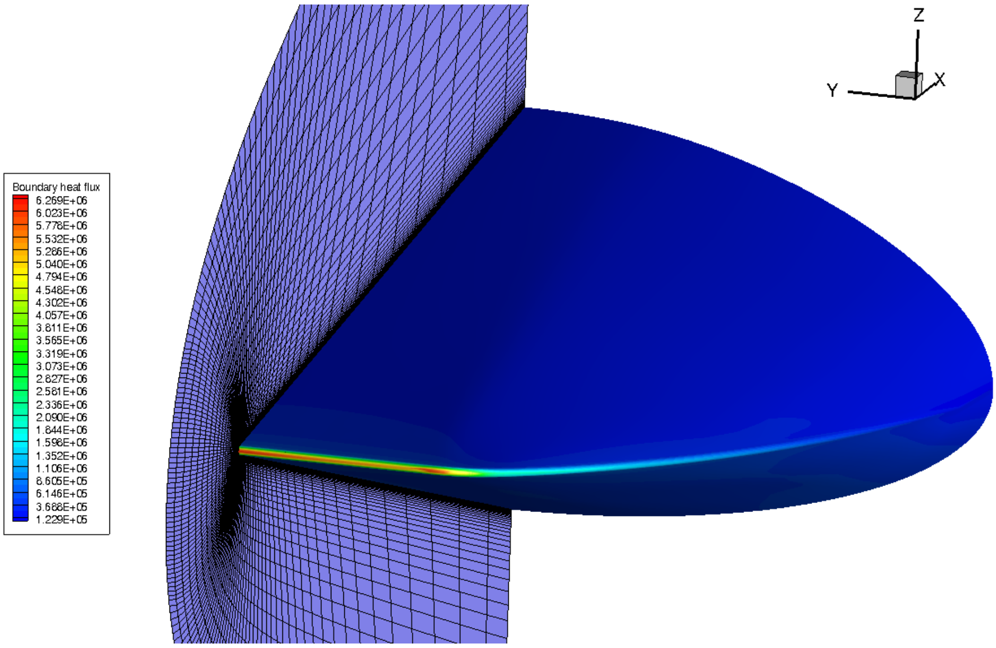

Figure 3: HEXAFLY-INT vehicle. Nose-only heat flux contours.

From the tables below (Table 2 and Table 3) we can see a comparison between the commercial code Fluent and the CIRA family code CAST (Rel. 14.5) for several test cases: first and second order, basic and shock-fitted grid, cold wall (T_{wall}=300 K) and radiative equilibrium wall (ε=0.8). Looking at HF results, we can deduce that the commercial code is less sensitive to the fitting of the grid and that in general the agreement between the codes is not so good and need more investigation. In particular, we can see that for what we should consider the best case (2nd order scheme and shock-fitted grid) we have a percentage difference of 14% and 20% between the two codes, respectively for the fixed temperature and radiative equilibrium cases.

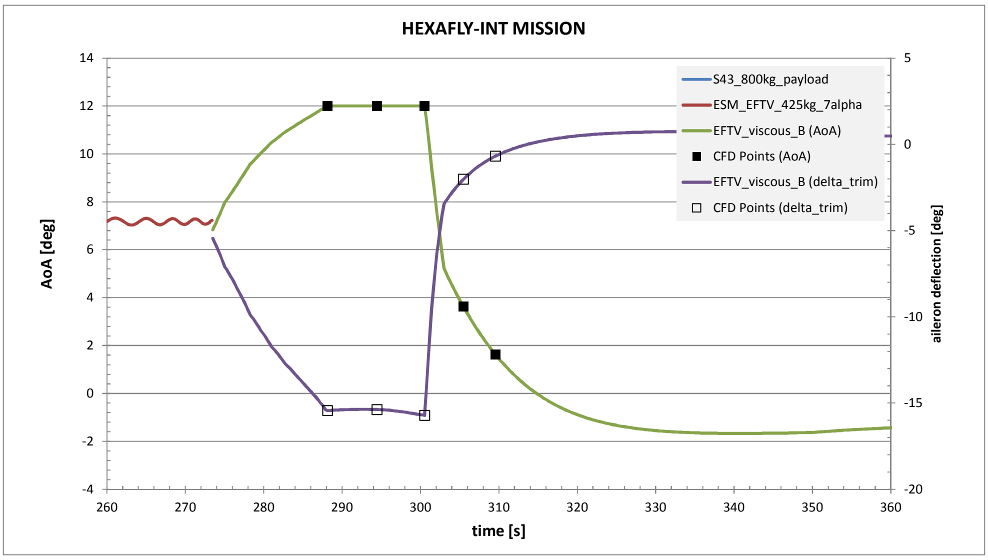

Figure 4: HEXAFLY-INT Trajectory. AoA and aileron deflection.

	FL1°	FL2°	FL fit1°	FL fit2°	Cast1°	Cast2°	Cast fit1°	Cast fit2°
HF *[W/m²]*	4585000	4795000	4267000	4492000	5634000	5617000	4692310	4823000
Press *[Pa]*	86656	85636	82323	85473	82569	88302	83657	83757

Table 2: Comparison between Fluent code (FL) and CIRA code CAST first and second order and non-fitted and fitted grid. T_{wall} = 300 K.

	FL1°	FL2°	FL fit1°	FL fit2°	Cast1°	Cast2°	Cast fit1°	Cast fit2°
HF *[W/m²]*	852370	789922	778305	809662	1134410	967766	975162	904865
Temp *[K]*	2082	2048	2035	2055	2225	2133	2150	2107
Press *[Pa]*	88003	82990	84850	86466	85690	83125	83454	82978

Table 3: Comparison between Fluent code (FL) and CIRA code CAST first and second order and non-fitted and fitted grid. Radiative Equilibrium at wall.

Being the radiative equilibrium hypothesis the basic boundary condition at wall that will be used for the EFTV aerodatabase simulations, a sensitivity analysis has been done for the emissivity coefficient whose value affects a lot the equilibrium temperature. The Zoby formula [10] has been used for the engineering evaluation:

$$HF = 3.88 * 10^{-4} * \sqrt{\frac{P_{t2}}{R_N}} * (H_0 - h_w) \ \frac{W}{m^2} \tag{1}$$

	FL fit2° eps=0.8	FL fit2° eps=0.4	Cast fit2° eps=0.8	Cast fit2° eps=0.4	Zoby eps=0.8	Zoby eps=0.4
HF *[W/m²]*	**809662**	**554331**	**904865**	**600560**	**762000**	466000
Temp *[K]*	**2055**	**2224**	**2107**	**2279**	**2025**	2128

Table 4: Comparison between CFD (Fluent and CAST) and Engineering formulas.

The differences between CFD and the engineering formula are due to the hypothesis of perfect gas with constant specific heat c_p used in the numerical data. For the engineering formula the far-field condition have been used for the computation of H_0 while for the wall enthalpy h_w has been computed with a local Cp that is higher than that of the far-field conditions. More accurate CFD simulations should consider a real gas state equation for the air with variable properties.

3.2 Full vehicle

The full vehicle computations aimed mainly at global aerodynamic coefficients evaluation at moment in longitudinal cases. The used grid is composed of about 3.5 million of cells (for half of the EFTV) and has a grid cell size of 10 micron (10^{-5} m). This grid size, sufficient for global parameters, seems to be not well appropriate for a good evaluation of local quantities, especially the heat flux. Table 5 reports a comparison between nose and full vehicle configuration. The “vehicle conf” heat flux values, extracted on the vehicle nosetip in the symmetry plane (y=0), are lower (about 13% for both thermal assumptions), and so not conservatives.

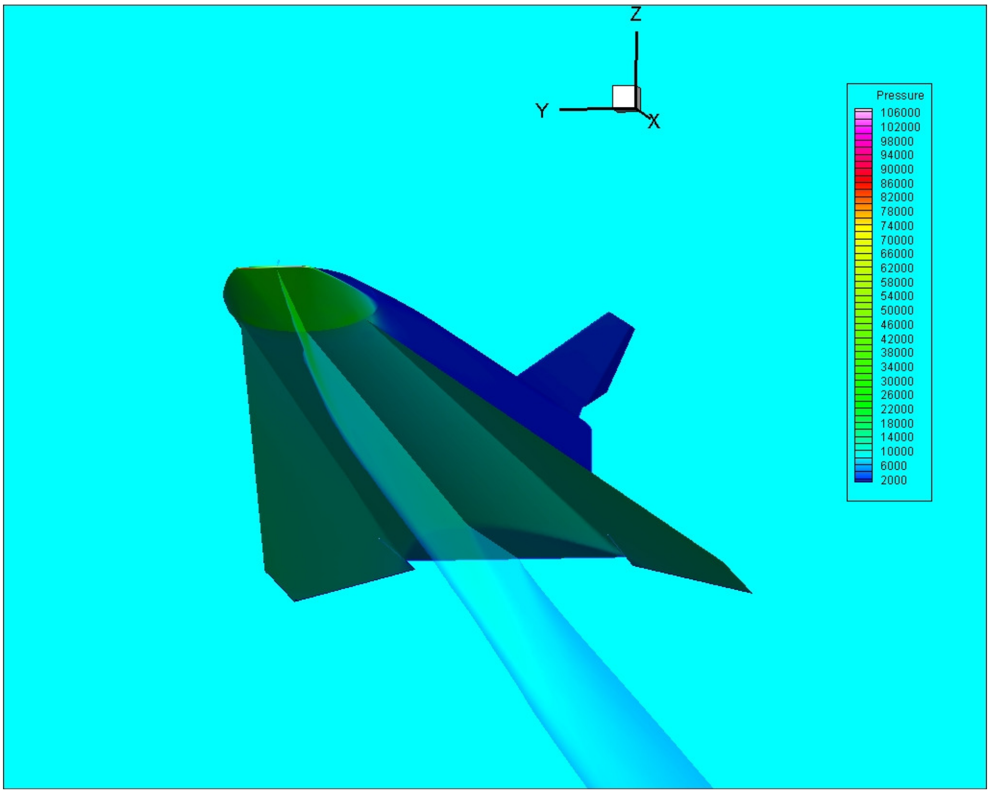

Figure 5: Pressure contour: AoA=12, Mach=7.25.

	Rad Eq		Fixed Temp	
	nose	vehicle	nose	Vehicle
HF *[W/m²]*	852370	742316	4585000	3973000
Temp *[K]*	2082	2011	(300)	(300)
Press *[Pa]*	88003	85912	86656	84739

Table 5: Comparison between "nose conf" and "vehicle conf" for aero-thermodynamic values on the nose. Both Radiative Equilibrium and Fixed Temperature at wall.

In the following figures (from Figure 6 to Figure 9), the main aerodynamic characteristics are reported. They have been computed with both the commercial code Fluent and the CIRA code (CAST). Showing a good comparison.

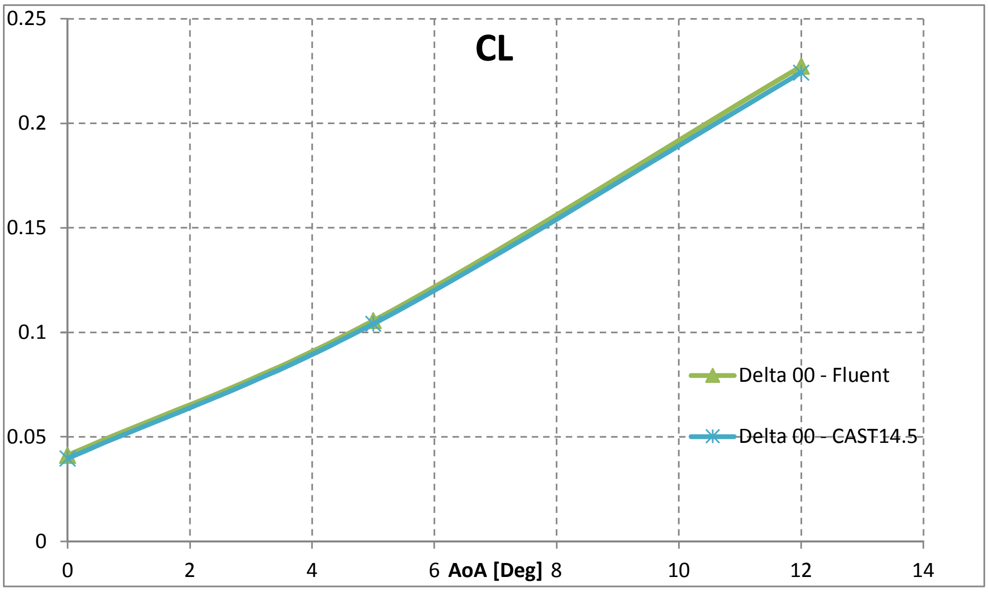

Figure 6: Lift Coefficient for clean configuration.

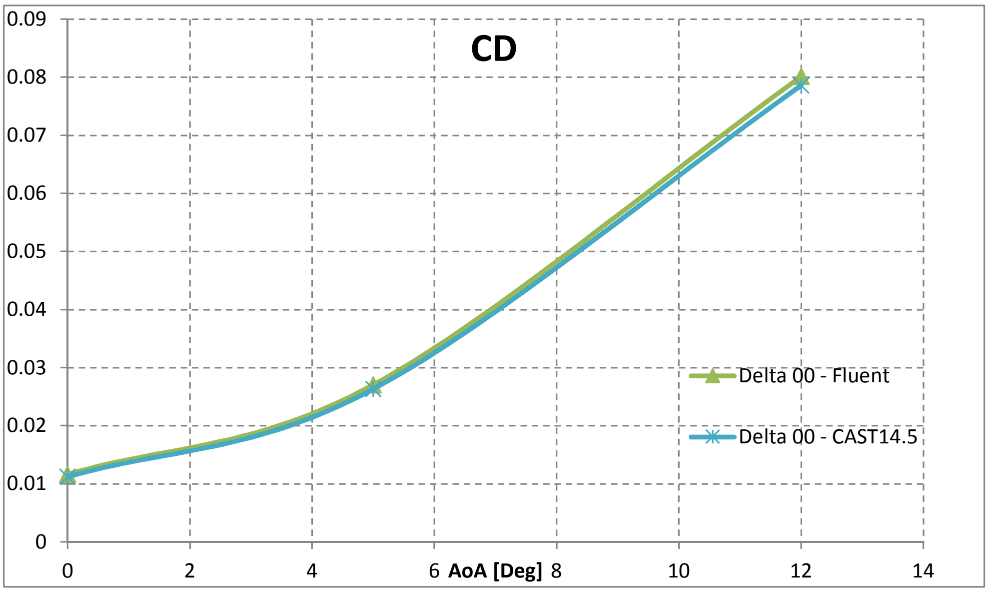

Figure 7: Drag Coefficient for clean configuration.

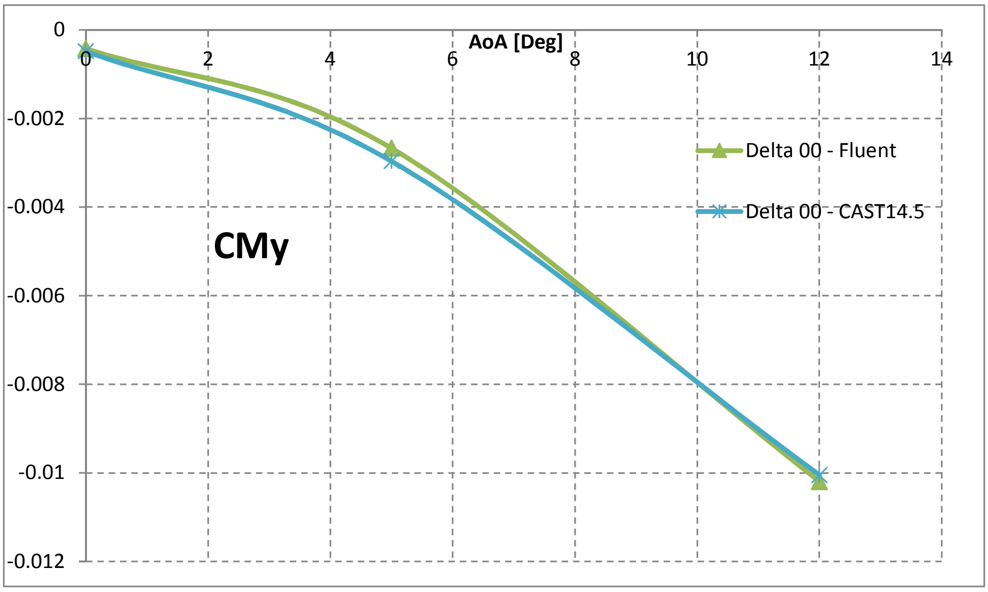

Figure 8: Pitching Moment Coefficient for clean configuration.

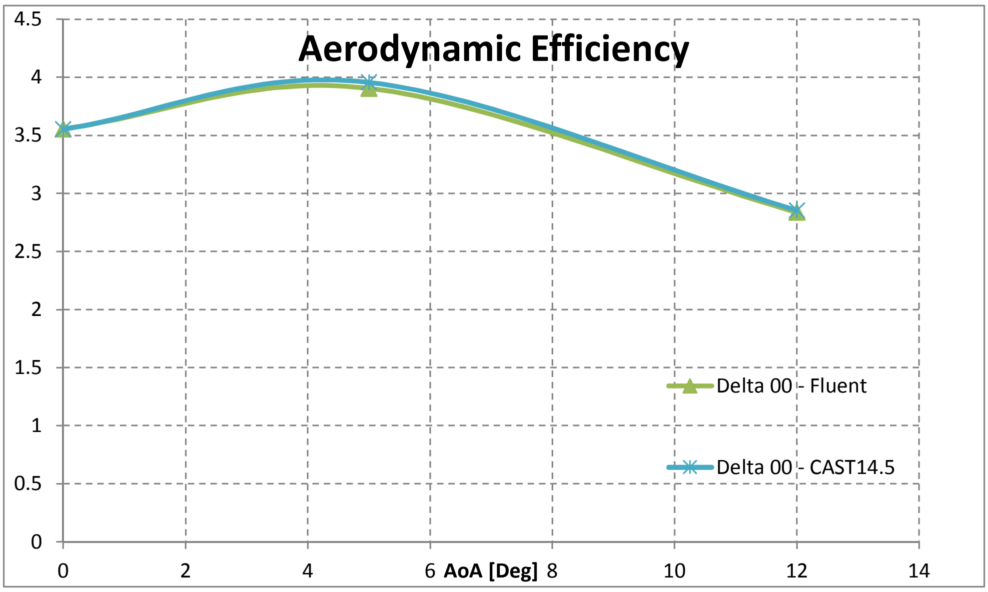

Figure 9: Aerodynamic Efficiency for clean configuration.

After the code-code comparison, a study of the behavior of the global coefficients versus the flap deflection has been also reported (see Figure 10 to Figure 13).

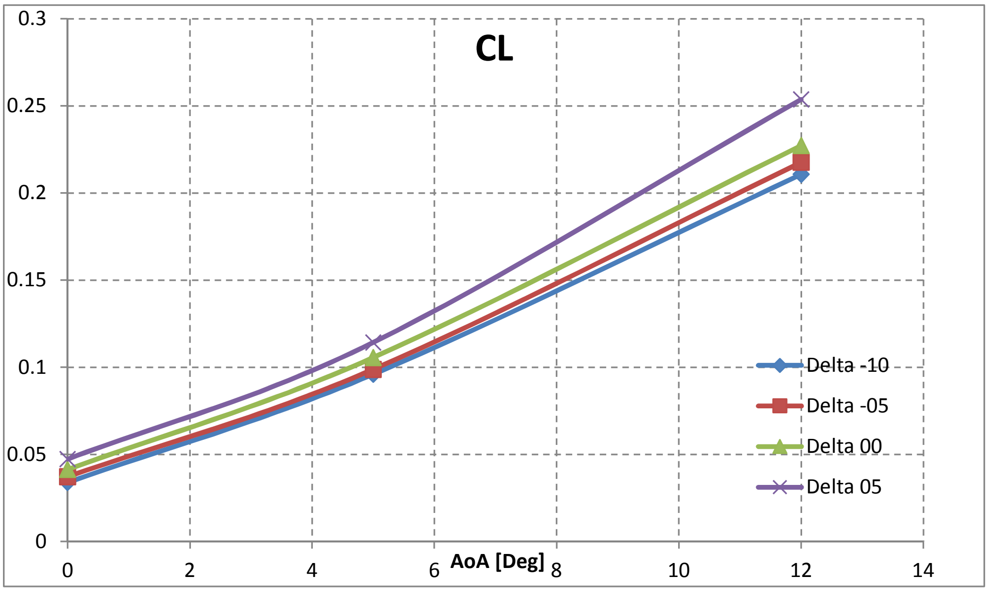

Figure 10: Sensitivity analysis of lift coefficient vs AoA for several delta-flap.

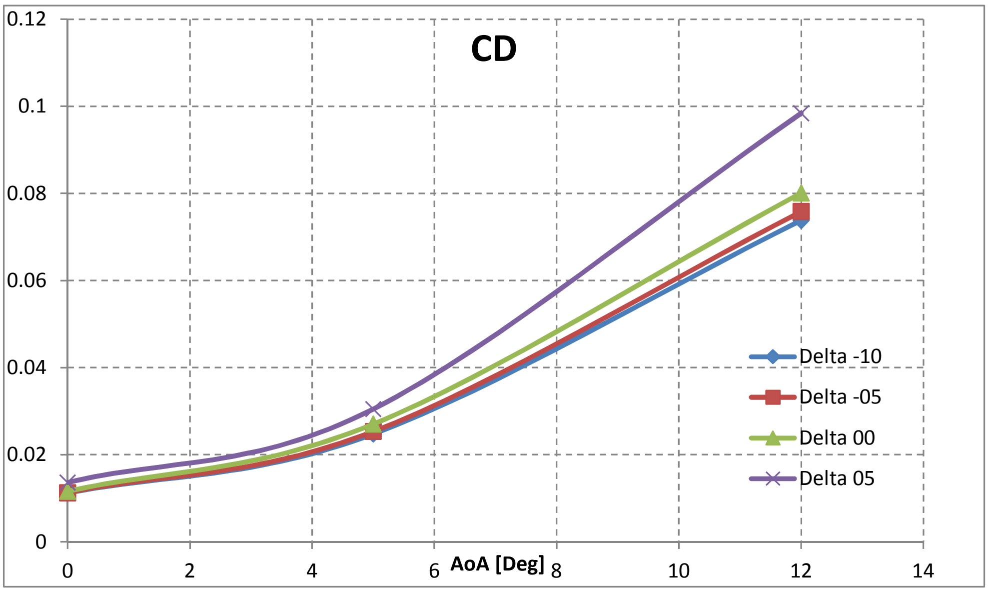

Figure 11: Sensitivity analysis of drag coefficient vs AoA for several delta-flap.

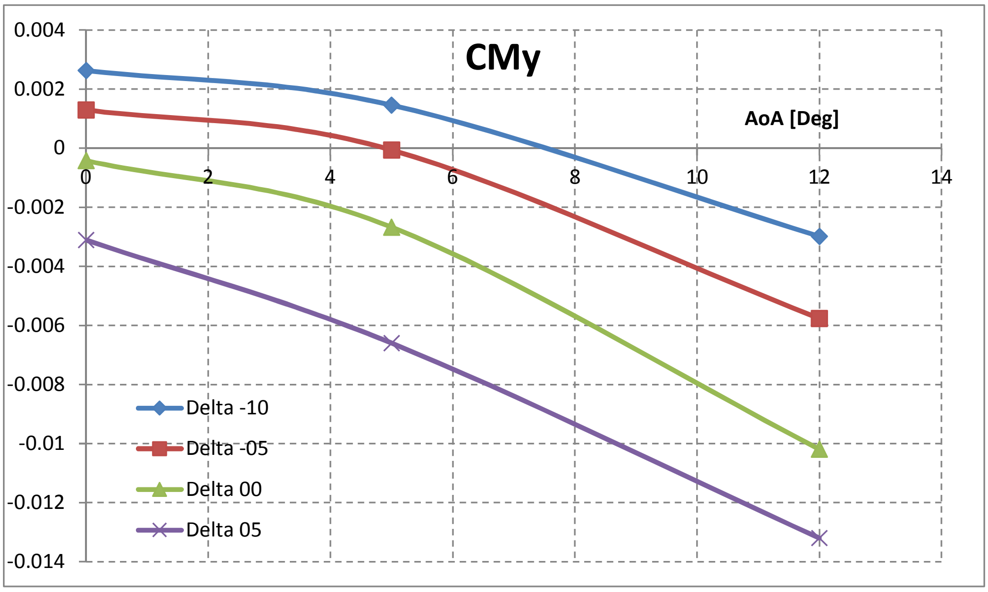

Figure 12: Sensitivity analysis of pitching moment coefficient vs AoA for several delta-flap.

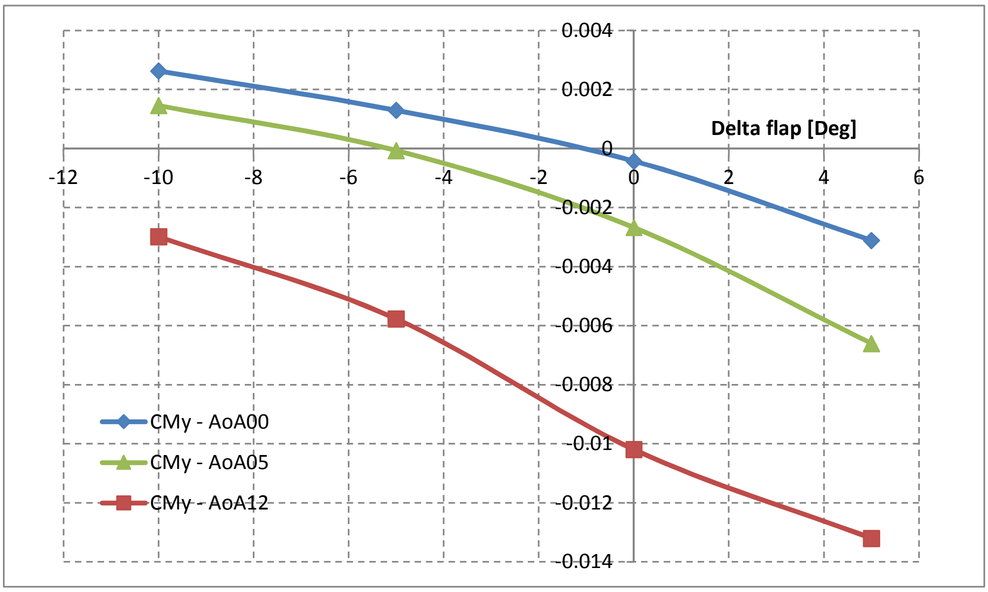

Figure 13: Sensitivity analysis of pitching moment coefficient vs delta-flap.

4 CONCLUSIONS

The present research effort dealt with an assessment analysis of computational fluid dynamic activity to be performed during the second phase of the EU-FP7 HEXAFLY-INT project. It focused on EFTV glider vehicle in the segment of trajectory dedicated to the in-flight experiment.

The nose computations showed the differences between several numerical techniques and codes and gave reliable computation of the nose heat fluxes being with this configuration possible an easily handling of the shock fitting, very important for this scope.

The full vehicle computations, performed with the assessed CFD methodology of the previous point, aimed above all at the characterization of the global aerodynamic coefficients versus the angle of attack and aileron deflection. A good code-code comparison resulted from the computation that makes us quite confident for what concerns the aerodynamic database generation.

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