Numerical and Experimental Aerodynamic Characterization of the HEXAFLY-INT Hypersonic Glider

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As a fundamental step towards the development of a civil high-speed transport concept, the European Community (EC) co-funded HEXAFLY-INT international project (with partners from Europe, Russian Federation, Brazil and Australia), has the aim to design, manufacture and test in flight an innovative gliding hypersonic vehicle, based on the configuration developed in previous EC co-funded projects LAPCAT I, II and HEXAFLY.

The flight experiment is focused on a self-controlled glider configuration characterized by high aerodynamic efficiency and equipped with several breakthrough technologies on-board, in order to provide valuable aerodynamic and aero-structural flight data to validate methods and technologies used to design the hypersonic vehicle.

In this framework, this paper provides a detailed overview on research efforts carried out in assessing the aerodynamic performance of the expendable Experimental Flight Test Vehicle under development in the programme. Aerodynamic results are obtained by means of a massive number of CFD simulations of increasing level of accuracy and through an experimental test campaign carried out at TsAGI in their T-116 wind tunnel facility.

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Nomenclature

$AEDB$	=	AErodynamic DataBase
AoA	=	angle of attack
AoS	=	angle of sideslip
b	=	wing span
C_A	=	axial force coefficient
C_D	=	drag force coefficient
C_L	=	lift force coefficient
C_l	=	rolling moment coefficient
C_M, C_m	=	pitching moment coefficient
C_N	=	normal force coefficient
C_n	=	yawing moment coefficient
C_Y	=	side force coefficient
CFD	=	computational fluid dynamics
D	=	aerodynamic drag, diameter
E	=	lift-to-drag ratio (aerodynamic efficiency)
H, h	=	altitude, height
Kn	=	Knudsen number
L	=	length, aerodynamic lift, vehicle length
L/D	=	aerodynamic efficiency (lift-to-drag ratio)
M	=	Mach number, pitching moment, mass
P	=	pressure
Pr	=	Prandtl number
Re	=	Reynolds number
S	=	surface
V	=	velocity
X, Y, Z	=	coordinates
WT	=	wind tunnel

Greek Symbols

α	=	angle of attack
β	=	angle of sideslip
Δ	=	variation
δ	=	aileron deflection
λ	=	molecular mean free path
ρ	=	density

I. Introduction

CIRA, the Italian Aerospace Research Centre, with the European Space Agency (ESA) and several European partners, is conducting in the frame of 7th Framework program a dedicated research project to develop the HEXAFLY-INT (High-Speed Experimental Fly Vehicles- INTernational) vehicle¹.

This research programme, co-funded by ESA, aims at the free flight testing of an innovative high-speed streamlined glider with several breakthrough technologies on board. This approach will create the basis to gradually increase the TRL level relevant to the design of hypersonic vehicles.

In order to mature the HEXAFLY-INT project, a scientific mission profile was worked within a precursor, Level-0 project, called HEXAFLY. This included a proof-of-concept, based upon a preliminary design of a high-speed scramjet propelled flight test vehicle, the selection and integration of the ground-tested technologies developed within LAPCAT I & II, ATLLAS I & II and other national programs, and the identification of the most promising flight platform(s)²⁻¹¹. A waverider-like configuration, namely Experimental Flight Test Vehicle (EFTV), was selected to allow for a hypersonic cruise or acceleration flight within the atmosphere^{1,2}.

Over the last years, several innovative concepts of civil high-speed transportation vehicles were proposed⁸⁻¹¹. These vehicles have a strong potential to increase the cruise range efficiency at high Mach numbers, thanks to efficient propulsion units combined with high-lifting vehicle concepts.

Performing a test flight at hypersonic speed will be the only and ultimate proof to demonstrate the technical feasibility of these new promising concepts versus their range efficiency.

In this framework, this paper provides, after a general overview of the mission and vehicle requirements, a detailed overview on research efforts carried out in assessing the aerodynamic performance of the expendable EFTV, under development in the programme.

Aerodynamic results obtained by means of a massive number of CFD simulations with increasing level of accuracy, and through an experimental test campaign carried out at TsAGI in their T-116 wind tunnel (WT) facility, are provided and discussed in detail in the paper.

II. Vehicle Description and Mission Profile

The EFTV glider, shown in Figure 1, is a hypersonic waverider-like glider of 3.29 m long and with a wing span of about 1.24 m. The EFTV has a two-dimensional nosetip with a 2 mm rounding and 2 mm lateral fillet, while the wing is characterized by a 80 deg sweep angle, a 14 deg negative dihedral angle and a 1 mm rounded leading edge.

The vehicle is equipped by a couple of active ailerons (0.4 m long and 0.32 m wide), which can be deflected in a symmetric and asymmetric way, and a couple of fixed vertical fins for passive lateral-directional control characterized by a 68.5 deg sweep angle and a 54 deg angle formed between the two fins in the transversal plane.

The present aeroshape of the EFTV is the result of an evolution, fully described in Ref. 1 and Ref. 13, started at the project kick-off (April 2014). Following the indications suggested by the continuous aero-heating assessment, mainly the nosetip and forebody configuration, the wing leading edge and the wing-fuselage intersection, and the aileron shape and edges were adapted¹³.

Figure 1. EFTV three-view drawing.

The glider vehicle will be launched by a sounding rocket, the Brazilian VS43 launcher equipped by a 8-ton solid rocket motor, in a suborbital trajectory having an apogee at around 90 km and Mach 8.

The vertical launch is planned from the Centro de Lançamento de Alcântara (CLA) in Brazil. In the first part of the trajectory the EFTV is docked to an Experimental Support Module (ESM), see Figure 2, which will control vehicle's attitude at high altitude by means of a cold gas system (CGS) in combination with the advantages coming from the aerodynamic flare configuration¹.

Figure 2. EFTV+ESM configuration.

A qualitative mission scenario for the HEXAFLY-INT project with the most important flight phases is shown in the following Figure 3.

Figure 3. HEXAFLY-INT qualitative mission scenario.

As one can see, after a boost provided by an expendable launch vehicle equipped by a solid rocket motor (S43), bringing the scientific payload (EFTV+ESM) to about 90 km apogee, the EFTV will perform the early descent flight docked to the ESM and will undock at about 50 km altitude, thus performing a hypersonic cruise.

Details of the reference mission scenario are summarized from Figure 4 to Figure 6, where the preliminary reference trajectory is shown. Indeed, after the separation a pull-out manoeuvre brings EFTV to a hypersonic levelled flight at approximately Mach 7 and at an altitude of about 30 km.¹

Figure 4. Overall altitude time history.

The Mach number time history is shown in Figure 5, while the overall time histories of AoA and aileron trim deflections are provided in Figure 6.

Figure 5. Overall Mach number time history.

Note that these preliminary trajectories have been generated by DLR-Moraba related the launch vehicle, assuming a total payload weight of 800 kg (EFTV, ESM, launch vehicle service module, fairing) for the S43 booster. Gas Dynamics Ltd. (GDL) provided the follow-up trajectory for the joint EFTV+ESM combination from 60 km to 50 km altitude and for the EFTV after the separation from ESM from 50 km to about 20 km altitude.

Figure 6. Overall time histories of AoA and aileron trim deflection.

A. Flight regime assessment

During a re-entry, a vehicle can generally experience three main flow regimes according to Bird's classification¹². During the upper part of descent trajectory, one is faced with the free molecular and the transitional flow regime, whereas a continuum flow regime is experienced within the lower atmospheric layers (see Figure 7).

Figure 7. Flight regime assessment.

This figure provides the preliminary reference EFTV flight envelope (50 km-viscous B) in the Mach-Reynolds numbers map. The similarity parameter governing these different flow regimes is the Knudsen number, defined as (rarefaction parameter):

$$Kn_{\infty L_{ref}} = \frac{\lambda}{L_{ref}} = 1.25\sqrt{\gamma} \frac{M_{\infty}}{Re_{\infty L_{ref}}} \quad (1)$$

where L_{ref} is the characteristic length of the body and λ is the molecular mean free path. As shown in Figure 7, the region for $10^{-3} < Kn_{\infty} < 10$ is the rarefied-flow transition region. Figure 7 points out clearly that only continuum flow conditions are expected for the EFTV throughout its mission. As a consequence, the glider aerodynamic appraisal will be addressed for continuum flow conditions only. With this in mind, the Reynolds and Mach numbers scenarios are assessed to allow for defining vehicle aerodynamics. Indeed, the EFTV flight envelope in the altitude-velocity map is shown Figure 8, where iso-Mach and iso-Reynolds curves are also provided, as well.

Figure 8. Constant Mach and Reynolds lines in the altitude-velocity map.

III. Aerodynamic Database Development of EFTV Glider

The aerodynamic analysis of EFTV is reported hereinafter in term of lift (C_L), drag (C_D), side force (C_Y), rolling moment (C_l), pitching moment (C_m), and yawing moment (C_n) coefficients, which are calculated according to the following equations.

$$C_i = \frac{F_i}{\frac{1}{2} \rho_{\infty} V_{\infty}^2 S_{ref}} \quad i = L, D, Y \quad (2)$$

$$C_l = \frac{M_x}{\frac{1}{2} \rho_{\infty} V_{\infty}^2 b_{ref} S_{ref}} \quad (3)$$

$$C_m = \frac{M_y}{\frac{1}{2} \rho_{\infty} V_{\infty}^2 L_{ref} S_{ref}} \quad (4)$$

$$C_n = \frac{M_z}{\frac{1}{2} \rho_{\infty} V_{\infty}^2 b_{ref} S_{ref}} \quad (5)$$

The moment reference centre (MRC) for the calculation of the aerodynamic moment coefficients is shown in Figure 9 with respect to the Layout Reference Frame (LRF).

Figure 9. The Layout Reference Frame.

Thus, the MRC coordinates in LRF for the EFTV are (1.455, 0, 0.120) [m].

In particular, C_L and C_D are provided in the vehicle's wind reference frame (WRF), while C_Y , C_l , C_m , and C_n are evaluated in the vehicle's body reference frame (BRF) shown in Figure 10.

Figure 10. The wind reference frame (X_w, Y_w, Z_w) and the body reference frame (X_B, Y_B, Z_B).

A. General inputs for Aerodynamic Database generation

The following reference parameters have been considered for the generation of the Aerodynamic Database (AEDB) of EFTV (see Figure 11): $L_{ref}=3.29$ m (i.e. body length – longitudinal reference length); $b_{ref}=1.24$ m (i.e. wing span – lateral-directional reference length); $S_{ref}=2.52$ m² (i.e. vehicle planform area – reference area).

Figure 11. Reference quantities for EFTV aerodynamics.

B. Aerodynamic force and moments definitions and signs rules

In Figure 12 the adopted reference frame (BRF) with aerodynamic coefficients conventions are shown. The reference system for the aerodynamic data is a body-fixed axis system, compliant with the ISO 1151 standard.

Figure 12. Reference frame and aerodynamic coefficients convention.

Directions of force and moment coefficients on the figure are positive as shown in Figure 12. The following aerodynamic sign convention for forces, moments, velocities, and accelerations is adopted (see Figure 10 and Figure 12):

- Angle of attack (α) is positive when free stream arrives from down of the pilot;
- Sideslip angle (β) is positive when free stream arrives from right of the pilot;
- Aileron deflection angle (δ_a) is positive when trailing edge is down;
- Elevon deflection angle (δ_e) is positive when trailing edge is down;
- Axial force coefficient (C_A) is positive when force is pushing in front of vehicle toward the base;
- Normal force coefficient (C_N) is positive when force is pushing on belly side of vehicle toward up;
- Side force coefficient (C_Y) is positive when force is pushing on left side of vehicle toward the right;
- Rolling moment coefficient (C_l) is positive when right wing is down;
- Pitching moment coefficient (C_m) is positive when the aircraft puts the nose up;
- Yawing moment coefficient (C_n) is positive when right wing is backward.

Note that this is the convention usually adopted in flight mechanics. For the sake of clarity, additional illustrations about aerodynamic signs convention are also provided in Figure 13.

Figure 13. Aerodynamic coefficients convention and sign rule.

Therefore, the aerodynamic static stability conditions, expressed in terms of derivatives, are the following: $C_{m\alpha} < 0$, for longitudinal stability; and $C_{Y\beta} < 0$, $C_{n\beta} > 0$, $C_{l\beta} < 0$, for lateral-directional stability.

C. CFD Analysis

Glider aerodynamic database (AEDB) was setup by CIRA using a massive number of CFD computations performed by several programme's partners, as DLR, ESA, CIRA and TsAGI.

The detailed content of CFD test matrix performed by DLR is reported in Table 1, for a total number of 1305 CFD Eulerian simulations¹³.

Mach	AoA [deg]	AoS [deg]	δ [deg]	no. of runs
2÷9, $\Delta M=1$	-6÷12, $\Delta\alpha=2$	0	-20÷5, $\Delta\delta=5$	480
2÷9, $\Delta M=1$	-6÷12, $\Delta\alpha=2$	2	-20÷5, $\Delta\delta=5$	480
2÷8, $\Delta M=2$	0, 6, 12	4, 8	0	24
3, 5, 7	0, 6, 12	0, 4	$\delta_l=-5, \delta_r=-20, -15, -10, 5$ and $\delta_l=5, \delta_r=-20, -15, -10$	126
7	0, 6, 12	-4	$\delta_l=5, \delta_r=-20$	3
3, 5, 7	0, 6, 12	0	-25	9
3, 5, 7	0, 6, 12	2	-25	9
3, 5, 7	0, 6	4	-25, -15, -10, -5, 5	30
3, 5, 7	0, 6	2	$\delta_l=-25, \delta_r=-20, -15, -10, -5, 5$	60
3, 5, 7	0, 6	0, 4	$\delta_l=-20, \delta_r=-10, 5$ and $\delta_l=-5, \delta_r=-20$	36
3, 5, 7	0, 6	-4	$\delta_l=-25, \delta_r=-10$ and $\delta_l=-20, \delta_r=-10, 5$ and $\delta_l=-5, \delta_r=-20, -10, 5$ and $\delta_l=0, \delta_r=-20, -15$	48

Table 1. Inviscid AEDB by DLR.

In order to improve this Eulerian aerodatabase (see Table 1), an additional 236 fully turbulent CFD simulations were performed ESA, CIRA and TsAGI summarized in both Table 2 and Table 3.

A first set of computations (Block#9) was performed by CIRA along a preliminary EFTV reference trajectory, whose test matrix is reported in Table 2, with three main objectives:

- ✓ to verify the trim conditions along the preliminary reference trajectory;
- ✓ to provide mechanical and thermal loads as inputs for thermo-structural analyses;
- ✓ to provide surface distribution of pressure, heat flux and temperature for the in-flight measurement system design and layout optimization (DRL-Cologne).

	Run ID	H (m)	V (m/s)	ρ (kg/m ³)	T (K)	M	AoA (deg)	P (Pa)	δ (deg)	Re _L	H ₀ (MJ/kg)
EFTV/ESM separation	EFTV-065	49942.00	2333.80	0.00104	270.65	7.076	6.83	80.359	-5.46	4.665E+05	2.99
	EFTV-066	37716.85	2337.68	0.00560	244.03	7.465	12.00	392.181	-15.44	2.746E+06	2.98
maximum Mach	EFTV-067	35947.24	2325.39	0.00732	239.14	7.501	12.00	502.252	-15.39	3.630E+06	2.94
maximum heat flux @ nosetip	EFTV-068	33059.99	2288.09	0.01147	231.14	7.507	12.00	760.605	-15.38	5.754E+06	2.85
maximum AoA, g-load	EFTV-069	29936.43	2187.90	0.01859	226.45	7.253	12.00	1208.457	-15.72	9.075E+06	2.62
maximum L/D	EFTV-070	28652.17	2136.93	0.02267	225.17	7.104	3.62	1465.014	-2.02	1.086E+07	2.51
	EFTV-071	28040.09	2112.00	0.02493	224.57	7.030	1.63	1606.457	-0.68	1.182E+07	2.46
maximum dyn. pressure, Re _c	EFTV-072	27461.55	2066.64	0.02727	223.99	6.888	-0.66	1753.112	0.41	1.269E+07	2.36
	EFTV-073	27444.96	1928.32	0.02734	223.98	6.427	-1.63	1757.515	0.64	1.187E+07	2.08
	EFTV-074	28854.96	1446.28	0.02197	225.37	4.806	0.51	1421.038	-2.25	7.115E+06	1.27
	EFTV-075	25720.26	1034.27	0.03580	222.27	3.461	0.97	2283.671	-5.04	8.388E+06	0.76
end of mission	EFTV-076	20384.69	591.17	0.08360	216.97	2.002	1.31	5206.060	-6.17	1.142E+07	0.39

Table 2. Viscous CFD by CIRA (Block#9).

After these preliminary computations, a more complete test matrix was simulated by CIRA, ESA and TsAGI in order to improve the glider aerodatabase and possibly reduce the uncertainties with respect to the first version¹⁴. The complete set of computations is summarized in Table 3.

Block	Runs	CIRA	ESA	TsAGI
1: A.M. (M, AoA, aileron) #1	120	60 @ Ma 2, 6	60 @ Ma 4, 7.5	
2: A.M. (sideslip)	24		24 @ Ma 4, 7.5	
3: A.M. (asym. ailerons)	12		12 @ Ma 4, 7.5	
4: M.U. (Re effect)	12			12
5: M.U. (Grid effects, unstructured)	9			9
6: M.U. (Turbulence mod.)	18			18
7: M.U. (LtT transition)	18			18
8: M.U. (code-to-code)	11 (of block#1)	4 @ Ma 4, 7.5 2 AoAs, 1 flap	4 @ Ma 2, 6 2 AoAs, 1 flap	3* (TBD)
9: Trajectory verification (Final)	12	12		
TOTAL	236	76	100	60

Table 3. Viscous CFD provided by ESA, CIRA and TsAGI.

As indicated by this test matrix, several fundamental aspects for AEDB development are addressed such as effects of Reynolds number, turbulence models, laminar-to-turbulence transition, different CFD numerical grids as well as code-to-code comparisons.

CIRA simulations were performed with the commercial code ANSYS FLUENT®, assuming a perfect gas behaviour with specific heat at constant pressure modelled with a polynomial function of temperature. For the turbulent cases the Spalart-Allmaras model was used, while the wall has been assumed in radiative equilibrium condition, with surface emissivity coefficient $\epsilon=0.4$ (except for $M=2$ case where adiabatic wall boundary condition was considered)¹⁴.

Computational unstructured grids have a typical dimension of about 10-million cells for half configuration. Examples of surface grid and pressure contours are shown in Figure 14 and Figure 15, while in Figure 16 wall pressure and heat flux profiles on the symmetry plane for most of the simulated conditions of Table 2 are plotted¹⁴.

Figure 14. EFTV surface grid.

Figure 15. EFTV surface temperature contours (29.93 km, $M=7.25$, $AoA=12$ deg, $\delta_e=-15.72$ deg) on full vehicle (left) and vehicle's forebody region (right).

Figure 16. EFTV pressure (left) and heat flux (right) distributions at Y=0.0 m section.

The simulations by ESA were based on a hybrid grid of varying sizes between 4.4 and 5.6 million nodes (12.2 to 16.2 million elements) depending on the aileron deflection angle. A full domain, roughly twice as large, was considered for the cases of sideslip angle and asymmetrical flap deflection.

The surface grid was unstructured triangular but for the leading edges of nose, wings, ailerons and vertical fins. A structured-squared grid was considered for improved reconstruction of the peak heat fluxes over these surfaces. The grid refining in the boundary layer consisted on a prismatic extrusion of the surface mesh up to 37 mm or 55 mm from the wall, depending on the first cell height. The height of the first cell ranged from 10 μm to 15 μm (decreased further to 5 μm on the leading edges). The prismatic extrusion comprised 40 cells with increasing height from the wall at a stretching ratio of 1.17.

For example, Figure 17 shows an overview of the surface and prismatic meshes (on the left), with detail of the mesh at the fuselage/aileron gap (on the right).

Figure 17. EFTV surface and prismatic meshes (left) and mesh enlargement at the fuselage/aileron gap (right).

The flow field was resolved with the code TAU of DLR¹⁵. The air thermal and transport properties were computed under the assumption of chemical equilibrium with five species, namely N_2 , O_2 , NO , N and O .

The originally proposed model by Spalart and Allmaras provided the turbulent closure of the RANS equations¹⁶. Since the laminar Pr number varies accordingly to the equilibrium model, a constant laminar to turbulent Prandtl number ratio of 0.8 was set to better approximate the turbulent part of the heat flux. The eddy to laminar viscosity ratio was set to 0.1 at the far-field and inflow boundaries.

The fluxes in the Navier-Stokes equations and the eddy viscosity model were discretized accordingly to the upwind second-order AUSMDV scheme by Wada and Liou with a shock fix to prevent the carbuncle phenomenon¹⁷. A least-square reconstruction of the gradients is used, which proves more accurate than the Green-Gauss approach in case of hybrid grids¹⁸. Finally, the RANS equations were integrated towards the steady solution by means of a backward Euler time-relaxation scheme¹⁹.

In addition, an analysis of laminar-to-turbulence natural transition along the reference trajectory has been performed by means of engineering criteria^{7,8}.

TsAGI CFD simulations of Table 3 have been performed by using ANSYS FLUENT[®] too. Computational grids have been built with 6-million, 13-million and 26-million cells for the symmetric EFTV half-body configuration, in particular to assess the effects of grid resolution¹⁴. Apart from the standard Spalart-Allmaras model, also the $k-\omega$ SST (TM1) and the $k-\epsilon$ with the Menter-Lechner wall treatment (TM2) were used as turbulence models. With respect to transition modelling, the models implemented in ANSYS FLUENT[®] have been used: Langtry and Menter SST-Transition Model (Tran1) and Walters and Leylek $k-kl-\omega$ Transition Model (Tran2). Transition onset is completely automatic based on the Local Correlation-based Transition Modelling (LCTM) concept (Tran1) and the laminar kinetic energy (Tran2).

Standard ANSYS FLUENT[®] settings have been used for present simulations. Some exemplary results are shown in the following Figure 18 and Figure 19.

Figure 18. Predicted turbulent intensity (Tu) distribution in 3D volume (blue, $Tu < 0.5$; red, $Tu \geq 0.5$), $M=7.5$, $AoA=0$ deg. Langtry and Menter SST-Transition Model (left) and Walters and Leylek $k-kl-\omega$ Transition Model (right).

Figure 19. Reynolds number effect on C_D at $M=7.5$, $AoA=15$ deg (left) and turbulence modelling effect on C_D at $M=7.5$, $\delta_e=-15$ deg (right).

The main outcome of all these numerical results was that the glider is statically stable in both longitudinal and lateral-directional flight, at all Mach numbers under investigation and for all angles of attack (AoA), angles of sideslip (AoS), and aileron deflections preliminarily considered. Some relevant plots (extracted by inviscid AEDB) of the moment (pitching, C_m , and yawing, C_n) coefficients are reported in the following figures.

Figure 20. C_m versus AoA at different Mach numbers and with and without sideslip angle effects.

Figure 21. C_n vs. AoS at different AoA at Mach=3 (left) and Mach=8 (right).

D. Experimental Test Campaign

In order to verify the preliminary AEDB and to define a proper uncertainty model to be used in the trajectory calculation, an experimental test campaign was carried on by TsAGI in the supersonic and hypersonic wind tunnel T-116, characterized by a test chamber with a squared cross section of $1\text{ m} \times 1\text{ m}$ size¹⁴. The wind tunnel is a blow-down type exhausting into the atmosphere by the aid of ejectors. The working gas is air. It allows providing different types of tests with a Mach number range from 1.8 to 10. The duration of the runs is up to 7 minutes. To prevent condensation of the air components during test, the wind tunnel is equipped with electrical heaters. The total temperature ranges from 300 to 1075 K.

Table 4 reports the complete matrix of experimental tests while Figure 22 shows the EFTV 0.35 scale model (1.15 m length), installed in the wind tunnel on a tail sting. Aerodynamic forces and moments acting on the model were measured by an electromechanical balance. The base drag was excluded from the experimental data by measuring the base pressure on the model and making corresponding correction. So, the resulting experimental data on aerodynamic coefficients correspond to the condition if the base pressure on the model equals to the free-stream static pressure. Corrections were made also for taking into account the effects of gravity and sting deformation during tests.

N.	Type of tests	M	AoA [deg]	AoS [deg]	Aileron deflection on pitch [deg]	Asymmetric aileron deflection [deg]
1	Balance tests	3, 4, 5, 6, 7, 8	-6÷12	0	0	0
2	÷	4, 7	-6÷12	4	0	0
3	÷	4, 7	-6÷12	0	-18, -12, -6, 6	0
4	÷	4, 7	-6÷12	0	0	$\delta_{\text{left}} = -12^\circ, \delta_{\text{right}} = 12^\circ$
5	÷	7	-6÷12	4	0	$\delta_{\text{left}} = -6^\circ, \delta_{\text{right}} = 6^\circ$
6	÷	7	-6÷12	4	0	$\delta_{\text{left}} = -18^\circ, \delta_{\text{right}} = 6^\circ$
7	÷	5	-6÷12	4	0	$\delta_{\text{left}} = -6^\circ, \delta_{\text{right}} = 12^\circ$
8	÷	5	-6÷12	4	0	$\delta_{\text{left}} = -6^\circ, \delta_{\text{right}} = -12^\circ$

Table 4. Experimental tests performed at TsAGI.

Figure 22. Glider model for TsAGI T-116 wind tunnel test campaign.

The free-stream flow parameters realized for the EFTV Glider model tests are reported in Table 5. Simulated flight altitudes (by Reynolds numbers, taking into account the scale of the model) correspond fairly well to the expecting flight test conditions.

M	3.03	4.05	5.05	6.00	6.99	7.88
P _{tot} , atm	1.1	1.4	5.0	7.4	22.0	31.5
T _{tot} , K	300	300	455	485	675	825
Re _m *10 ⁻⁶	7.74	5.96	6.88	6.32	7.66	5.92
Simulated Flight Altitudes:						
H, km	24.8	28.0	28.4	30.5	30.0	32.5

Table 5. The flow parameters realized for Glider tests in T-116 wind tunnel.

Aerodynamic characteristics of the EFTV Glider obtained from tests at different Mach numbers without sideslip angle and without aileron deflection are shown on Figure 23 in terms of drag force coefficient C_D , aerodynamic efficiency L/D , and pitching moment C_m vs. angle-of-attack α . The maximum values of the aerodynamic efficiency varying from 4.0 to 4.5 were achieved at $\text{AoA}=2$ deg. The pitching moment characteristics are very similar to those obtained by CFD.

Figure 23. Experimental aerodynamic characteristics C_D (left), L/D (center) and C_m (right) vs. AoA at different Mach numbers without sideslip angle, clean configuration.

Figure 24 represents the experimental data on pitching moment coefficient C_m vs. symmetric aileron deflection δ at Mach numbers 4 and 7. According to these data, the EFTV glider can be trimmed at AoA range from -6 to $+6$ deg by aileron deflection from $+2.5$ to -16 deg at $M=4$, and from $+4$ to -12 deg at $M=7$.

Figure 24. Pitching moment coefficient vs. elevon deflection angle without sideslip at $M=4$, and 7 and different AoA.

IV. The Aerodynamic Model of the EFTV Glider

This section contains the EFTV Aerodynamic Model (AM) needed for the development of the vehicle aerodynamic database to be used for Flight Mechanics analysis, subsystem design and analyses, as well as for flight control analysis.

An important aspect of developing an aerodynamic database is the formulation of an aerodynamic model²⁰. For example, the accuracy of the database depends on the degree to which the AM represents the physics of the problem. Therefore, it is important that all the aerodynamic and control variables that may have influence on the given aerodynamic coefficient must be included in the aerodynamic model.

To this end, a number of hypotheses have been assumed in developing the EFTV AM. Indeed, the independent variables that were recognized as influent on the EFTV aerodynamic state are: Mach number, M , Reynolds number, Re , angle of attack, α , angle of sideslip, β , and aerodynamic surfaces deflection angles both as elevons, δ_e , and as ailerons, δ_a .

The couple (M, Re) identifies the aerodynamic environment while the remaining variables completely describe the flow field direction and vehicle state (i.e. configuration and attitude)²⁰. Therefore, the functional structure of the AM of EFTV is based on these independent variables.

In particular, as typically done in a classical approach, each aerodynamic coefficient can be derived by supposing that each contribution to the single global coefficient is treated independently from the others. This means, from an operational point of view, that each aerodynamic coefficient is described by a linear summation over a certain number of incremental contributions.

Each contribute is based on a small number of parameters, as recognized herein. Further, as done in the past for the US Orbiter and X-34 vehicles, the EFTV AM development relies on the following applicable assumptions²¹:

1. Only rigid body aerodynamic coefficients are evaluated, i.e., no aero-elastic deformations are accounted for;
2. No Reynolds number effects on aerodynamic control surfaces are assumed;
3. No sideslip effects on aerodynamic control surfaces are assumed;
4. No effects of protrusions, gaps and roughness are considered;
5. No mutual aerodynamic interference between various control surfaces is considered.

A. Development of Aerodynamic Database (AEDB_V2.0)

The aerodynamic characteristics pertaining to the longitudinal and lateral degrees of freedom are presented as full scale rigid force and moment coefficients²⁰. They are presented in a form allowing a build-up to any desired configuration and/or flight condition by incremental addition to the basic coefficient²⁰.

Each aerodynamic coefficient was considered separately by the appropriate equation in which appear all the pertinent contributions for obtaining the total coefficient for any selected flight condition. Each element of the equation is defined and referenced. Indeed, following the formulation used for the Space Shuttle and assuming that the vehicle is operating at a combined AoA and AoS, the total lift coefficient is given by:

$$C_{L,total} = C_{L,b}(\alpha, M) + \Delta C_{L,\delta_e} + \Delta C_{L,\delta_a} + \Delta C_{L,b,\beta} \quad (6)$$

where $C_{L,total}$ is the total coefficient of the vehicle for a given flight condition as expressed by the flight Mach number M, AoA α , sideslip β , elevon deflection δ_e , and ailerons deflections δ_a .

The parameter $C_{L,b}(\alpha, M)$ is baseline lift coefficient at zero sideslip and zero control surface deflections (i.e., in clean configuration). The parameter $\Delta C_{L,\delta_e}$ represents incremental lift coefficient due to symmetric elevon deflections above the baseline, and it is given by:

$$\Delta C_{L,\delta_e} = C_L(\alpha, M, \delta_e) - C_{L,b}(\alpha, M) \quad (7)$$

The parameter $\Delta C_{L,\delta_a}$ represents the incremental lift coefficient due to aileron (asymmetric elevons) deflections above the baseline and can be evaluated using the data on symmetric elevons as follows:

$$\Delta C_{L,\delta_a} = \left(\frac{\Delta C_{L,\delta_e=\delta_{e,L}} + \Delta C_{L,\delta_e=\delta_{e,R}}}{2} \right) - \Delta C_{L,\delta_e} \quad (8)$$

Here, we use the elevon data twice, once assuming $\delta_e=\delta_{e,L}$, and obtaining $\Delta C_{L,\delta_e=\delta_{e,L}}$, then assuming $\delta_e=\delta_{e,R}$, and determining $\Delta C_{L,\delta_e=\delta_{e,R}}$. As a check, when aileron deflection is zero, i.e., $\delta_e=\delta_{e,L}=\delta_{e,R}$, the value of $\Delta C_{L,\delta_a}$ vanishes as expected.

The incremental lift coefficient due to baseline (clean configuration) in sideslip are given by:

$$\Delta C_{L,b,\beta} = C_L(\alpha, \beta, M) - C_L(\alpha, M) \quad (9)$$

To get the incremental coefficient due only to sideslip β , we have to subtract the incremental due to AoA as shown by second term on the right hand side of equation. Those contributions represent aerodynamic cross coupling effects, and they have been found to be significant, especially at higher values of AoA.

In a similar fashion, we assume that the drag and pitching moment coefficients are given by:

$$C_{D,total} = C_{D,b}(\alpha, M) + \Delta C_{D,\delta_e} + \Delta C_{D,\delta_a} + \Delta C_{D,b,\beta} + \Delta C_{D,b,Viscous} \quad (10)$$

$$C_{m,total} = C_{m,b}(\alpha, M) + \Delta C_{m,\delta_e} + \Delta C_{m,\delta_a} + \Delta C_{m,b,\beta} \quad (11)$$

Viscous effects, included the term $\Delta C_{D,b,Viscous}$, have been then estimated by CIRA on the base of viscous CFD simulations^{13,14}. Indeed, a viscous correction was added only to axial force, assuming a flat plate with a total wetted area of 7.35 m². With this assumption, the skin-friction coefficient was evaluated by means of the modified Schlichting correlation²², to account for compressibility effects, i.e.

$$C_f = \frac{0,42}{\left(\log_{10}(Re_{Lref})\right)^{2,55} (1 + 0,25M_\infty^2)^{0,31}} \quad (12)$$

where ∞ stands for free-stream conditions.

The side force coefficient is assumed to be given by:

$$C_{Y,total} = C_{Y,b}(\alpha, M) + \Delta C_{Y,\delta_a} + \Delta C_{Y,b,\beta} = \Delta C_{Y,\delta_a} + \Delta C_{Y,b,\beta} \quad (13)$$

since the vehicle configuration is symmetric, i.e. $C_{Y,b}(\alpha, M) = 0$.

Further,

$$\Delta C_{Y,b,\beta} = C_{Y,b}(\alpha, \beta, M) - C_{Y,b}(\alpha, M) = C_{Y,b}(\alpha, \beta, M) \quad (14)$$

Similarly,

$$\Delta C_{Y,\delta_a} = C_Y(\alpha, M, \delta_a) \quad (15)$$

Then,

$$C_{Y,total} = C_{Y,b}(\alpha, \beta, M) + C_Y(\alpha, M, \delta_a) \quad (16)$$

Proceeding in a similar way, the rolling and yawing moment coefficients are assumed to be given by:

$$C_{l,total} = C_{l,b}(\alpha, \beta, M) + C_l(\alpha, M, \delta_a) \quad (17)$$

$$C_{n,total} = C_{n,b}(\alpha, \beta, M) + C_n(\alpha, M, \delta_a) \quad (18)$$

Therefore, it is assumed that the sideslip has effect only on the baseline, but it has no effect when elevons or ailerons are deflected. Moreover, no dependency on Reynolds number is assumed for the elevons/aileron contribution. Indeed, even though this effect exists, it is however small and difficult to be modeled. Then, it has been considered as part of the aerodynamic coefficients uncertainty.

This model was implemented in a numerical tool, developed in Matlab®, able to provide vehicle aerodynamic performance in points of the EFTV flight scenario where neither WT nor CFD data exist in a continuum fashion, thanks to its own polynomial formulation^{20,23}.

V. The Uncertainty Model for the EFTV Glider

In order to use the Aerodynamic Database for the trajectory generation, a proper uncertainty model is required^{20,24}. It is important to underline that the uncertainties must include two contributions: on one side the tolerances, that strictly depend on the accuracy of the numerical and physical modeling used for the computations and on the quality and accuracy of the

experimental data; on the other side there are the so called variations, that depend on the estimated possible differences between nominal and real flight conditions and are mainly based on the experiences of previous flights^{20,24}.

Within the design phase, it is important to take into account both terms, in order to design a more robust system and reliable control laws.

The generic coefficient C_i is written as:

$$C_i(\alpha, \beta, \delta_r, \delta_l) = C_{i,nom} \pm \Delta C_{i,unc} \quad (19)$$

while the related uncertainty reads as follows:

$$\Delta C_{i,unc} = \Delta C_{i,b,unc} + \Delta C_{i,\alpha,unc} * (\alpha - \alpha_{Ref}) + \Delta C_{i,\beta,unc} * \beta + \Delta C_{i,\delta_e,unc} * \delta_e + \Delta C_{i,\delta_a,unc} * \delta_a \quad (20)$$

where

$$\alpha_{Ref} = -4 \text{ for } C_L \quad ; \quad \alpha_{Ref} = -6 \text{ for } C_m \quad (21)$$

Based on the comparison between the AEDB nominal values and the experimental data, and on available data on other hypersonic vehicles, a first set of uncertainties was defined. These values could be slightly modified in the next iterations with the flight mechanics. The uncertainties for each coefficient are reported in the following Table 6.

	$\Delta C_{i,b,unc}$	$\Delta C_{i,\alpha,unc}$	$\Delta C_{i,\beta,unc}$	$\Delta C_{i,\delta_e,unc}$	$\Delta C_{i,\delta_a,unc}$
C_L	0.01	0.001		0.0003	
C_D	0.0075*	0.001			
C_Y	0.0005		0.001		0.0002
C_m	0.002**	0.0002		0.0001	0.0001
C_n	0.001		0.0002		0.0003
C_l	0.002		0.0003		0.0002

* This value is divided by 2 for negative uncertainty

** This value is divided by 2 for positive uncertainty

Table 6. Uncertainties for the aerodynamic database.

In the following figures, several comparisons between nominal AEDB coefficients and experimental data from TsAGI T-116 wind tunnel test campaign are shown.

Uncertainties given by the model explained previously have been also reported in the figures.

Figure 25. Comparison among AEDB, CFD, and WT data. Lift coefficient at M=6 (left) and M=4 (right), AoS=0 deg, clean configuration.

Figure 26. Comparison among AEDB, CFD, and WT data. Drag coefficient at $M=6$ (left) and $M=3$ (right), $AoS=0$ deg, clean configuration.

Figure 27. Comparison among AEDB, CFD and WT data. Pitching moment coefficient at $M=6$ (left) and $M=4$ (right), $AoS=0$ deg, clean configuration.

Figure 28. Comparison among AEDB, CFD, and WT data. Side force coefficient at $M=7$ (left) and $M=4$ (right), $AoS=4$ deg, clean configuration.

Figure 29. Comparison between AEDB and WT data. Rolling moment coefficient at M=7 (left) and M=4 (right), AoS=4 deg, clean configuration.

Figure 30. Comparison between AEDB and WT data. Yawing moment coefficient at M=7 (left) and M=4 (right), AoS=4 deg, clean configuration.

Figure 31. Comparison among AEDB, CFD, and WT data. Rolling moment coefficient (left) and yawing moment coefficient (right), M=7, AoS=4 deg, $\delta_{e,L}=-6$ deg, $\delta_{e,R}=6$ deg.

VI. Concluding Remarks

The present paper has dealt with the aerodynamic performance analysis of the experimental flight test vehicle under development in the seventh framework programme, namely HEXAFLY-INT. A mission scenario, the different flight segments and events to which the payload is exposed were described and justified. This allowed defining the aero-thermo-mechanical loads required to conceptually design all on board systems of the vehicle.

This flying test bed is a self-controlled glider configuration aiming to a levelled hypersonic flight at about Mach 8 and 30km altitude, followed by a gliding descent combined with a banking manoeuvre up to the vehicle loss. During this flight, several experiments shall be carried out. The appraisal of the vehicle aerodynamic performance is needed for Flight Mechanics and Guidance, Navigation and Control analysis. In particular, hinge line moments for the glider aileron were also addressed to design the actuation lane and to select the actuator device itself. The vehicle design has made maximum use of databases, expertise, technologies and materials elaborated in previously European community co-funded projects ATLLAS I & II, LAPCAT I & II and HEXAFLY.

Numerical results have pointed out the compliance of vehicle's aerodynamic performance with the flight envelope expected for the glider.

Aerodynamic results highlighted that vehicle aeroshape features a lift-to-drag ratio greater than 4 for Mach ranging from 6 to 8 and angle of attack from -1 to 7 deg. No significant effects of sideslip on aerodynamic efficiency, total pitching moment and map of trim-ability were predicted. Moreover, the glider is statically stable both in longitudinal and lateral-directional flight conditions with the provided moment reference point for positive angles of attack, and is trimmable in pitch in most of the flight conditions investigated in the present research effort.

An aerodynamic model for the glider, with related uncertainties, was built based upon a more populated aerodynamic database with viscous effects and results of TsAGI wind tunnel campaign at T-116 facility. This model plus uncertainties will serve Flight Mechanics for the calculation of the EFTV glider final trajectory with related dispersion and for the design of Flight Control System.

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