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AERODATABASE DEVELOPMENT AND INTEGRATION OF SUPERSONIC/HYPERSONIC CRUISER VEHICLES IN MORE&LESS PROJECT

P. Roncioni[1], M. Marini[1], R. Fusaro[2], N. Viola[2]

[1] CIRA – Italian Aerospace Research Centre, Capua (CE), Italy
[2] Mechanical and Aerospace Engineering Department, Politecnico di Torino, Italy

Abstract

This paper deals with the development and integration of increasing-fidelity aerodynamic modelling approaches in the conceptual design of hypersonic cruisers. At this purpose, a dedicated methodology has been developed in the framework of the H2020 More&Less project and applied to several supersonic/hypersonic vehicles. This methodology foresees the development of aerodynamic aerodatabases by means of incremental steps starting from simplified methods (panels methods and/or low fidelity CFD simulations) up to very reliable data based on high fidelity CFD simulations and experimental measurements with associated confidence levels. This allows us to follow the development phases of the vehicle all along the entire design cycle by providing preliminary aerodynamic coefficients at initial conceptual approach and so very tailored aerodatabases at advanced design phases. For each design stage, a build-up approach is adopted from the clean external configuration up to the complete configuration, including Control Surfaces effects and, if any, the Propulsion Systems Elements to be considered in order to have a full characterization of forces and moments acting on the vehicle.

Keywords: Aerodynamic Characterization; Hypersonic civil transport, MORE&LESS

1. Introduction

The European Commission is funding the H2020 MORE&LESS Project (MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation) ([1]), aiming at developing a wide design platform for future supersonic aviation on the base of global environmental regulations. A multi-disciplinary optimization framework to assess the holistic impact of supersonic aviation onto environment is foreseen that can incorporate high-fidelity modelling activities and test campaigns. At first, different disciplines will tackle separate design topics through modelling and tests and then the environmental impact of these aircraft concepts will be evaluated through the holistic framework.

To further extend the validity of theories and models, the entire spectrum of supersonic speed regime ranging from Mach 2 to Mach 5 is considered. Moreover, the analysis is not only restricted to aircraft using traditional hydrocarbon fuels, but it moves beyond, addressing aircraft concepts exploiting alternative fuels, such as biofuels and cryogenic fuels. The idea of considering more case-studies (CS) with different configurations, performance and fuels fosters the enhancement of the flexibility of the tools, which, starting from the case-studies, are developed based on modelling activities and test campaigns as products that can be flexible enough to be applied to several future vehicle concepts.

In order to achieve this aim one important activity is the development of the aerodynamic database. This paper deals with the development and integration of increasing-fidelity aerodynamic modelling approaches in the conceptual design of hypersonic cruisers. This methodology foresees the development of aerodynamic aerodatabases by means of incremental steps starting from simplified methods (panels methods and/or low fidelity CFD simulations) up to very reliable data based on high fidelity CFD simulations and experimental measurements with associated confidence levels. This allows us to follow the development phases of the vehicle all along the entire design cycle by providing preliminary aerodynamic coefficients at initial conceptual approach and so very tailored aerodatabases at advanced design phases.

For each design stage, a build-up approach is adopted that accounts for several contributions linearly added each other, from the clean external configuration up to the complete configuration, including Control Surfaces effects and, if any, the Propulsion Systems Elements in order to have a full characterization of forces and moments acting on the vehicle.

2. Aerodatabase Building

The aerodatabase of a generic high-speed civil aircraft considered in the framework of the project is built with increasing fidelity steps starting from preliminary aerodynamic data obtained by means of inviscid CFD and/or panels methods up to final and more reliable aerodatabase with viscous CFD and experimental measurements and associated confidence level bars.

2.1 Low fidelity ADB

At the first stage, the aerodynamic modelling consists in the investigation of the clean configuration (with undeflected control surfaces). Based on the experience gained in the H2020 STRATOFLY project (Figure 1) inviscid CFD simulations are used on the clean configuration and then viscous effects corrections are applied [3]. These corrections can be estimated through engineering formulations, which are widely available in literature and whose coefficients can eventually be tuned to the current vehicle.

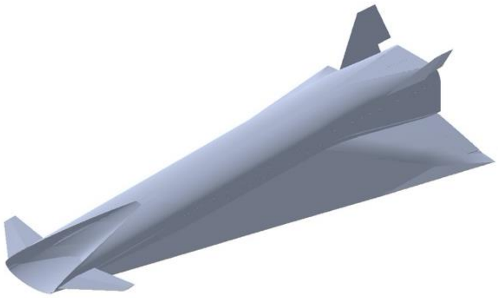

Figure 1 – STRATOFLY MR3 external layout and main dimensions.

It is important noticing that Supersonic/Hypersonic Panels Method (Surface Impact Method tool), based on classical Modified-Newtonian, Tangent-Wedge and Shock-Expansion Theories are widely used in these preliminary design stages. Even if these theories and tools provide a valuable support for the aerodynamic characterization of high-speed vehicles throughout the supersonic and hypersonic speed regimes, they cannot be used to predict the behaviour of such vehicles along the transonic and subsonic phases. Therefore, inviscid CFD simulations have been preferred.
The viscous effect engineering formulation ([11] [13] [14]) can be generalized as it follows:

$$(\Delta C_D)_{visc_{ext}} = \alpha * \frac{1}{[Log(Re)]^{2.58}} * \frac{1}{(1+\beta * M^2)^{\gamma}} * \frac{A_{wet}}{A_{ref}}, \tag{1}$$

The parametric formulation reported in Eq. (1) allows for the estimation of the viscous effect by correcting the turbulent flat plate theory (represented by the term $\frac{1}{[Log(Re)]^{2.58}}$, see [11]) with (i) the factor $\frac{1}{(1+\beta * M^2)^{\gamma}}$ which takes into account the compressibility effect ([13]), (ii) the wetted-to-reference area ratio. The parameters α, β, γ shall be customized depending on the vehicle configuration. For example, the values $\alpha = 0.43, \beta = 0.31$ and $\gamma = 0.37$ have been found for STRATOFLY MR3 configuration.
The general formulation is synthetized in the following formulations (for the longitudinal flight and body axis reference frame), where the nominal coefficients are obtained as a sum of several contributions: clean configuration, control surfaces deflection (the summations), viscous and thrust effects:

$$C_N = (C_N)_{clean} + \sum_{i=1}^{n} (\Delta C_N)_i$$

$$C_A = (C_A)_{clean_{inv}} + (\Delta C_A)_{visc_{ext}} + (\Delta C_A)_{visc_{int}} + \sum_{i=1}^{n} (\Delta C_A)_i$$

$$C_{My} = \left(C_{My}\right)_{clean} + \sum_{i=1}^{n} \left(\Delta C_{My}\right)_i + \left(\Delta C_{My}\right)_{Thrust}$$

In Figure 2 some of the supersonic configurations to be analysed are shown. On the left a Mach 2 "Concorde-like" with biofuel as propellant, and on the right an experimental Mach 5 Hypersonic Test Bed (HTB) by Reaction Engines Ltd. fuelled with liquid hydrogen.

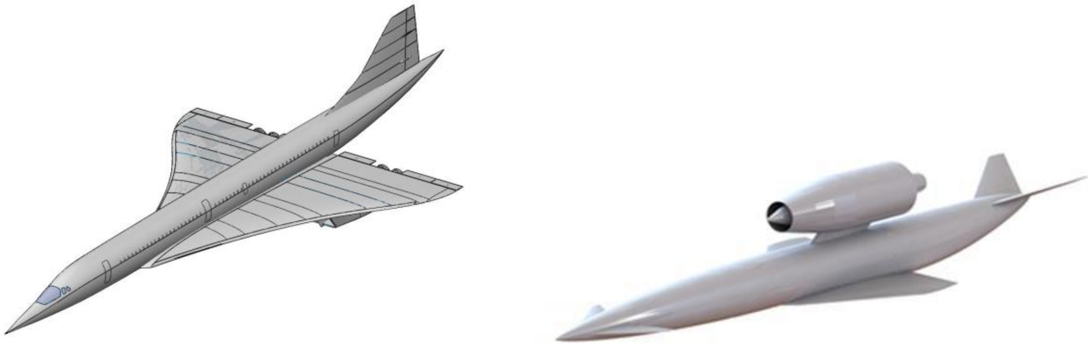

Figure 2 – Some of the configurations to be analyzed. CS1 (left), CS2 (right)

2.2 High fidelity ADB

After the preliminary studies a more reliable aerodatabase is needed in order to refine the design of the aircraft and related mission. The high-fidelity ADB is based on viscous CFD computations and experimental measurements.

The final data provide the nominal aerodynamic coefficients with including an appropriate uncertainty level ([11]). The choice of nominal values depends on the approach followed for the building of the coefficients. Usually large experimental campaigns are foreseen and then these values, suitably corrected from wind tunnel errors, are used as nominal values. However, a different approach can be followed if a large test campaign is not foreseen neither for CFD computations nor for experimental measurements. In this paper since a full aerodatabase has to be developed by means Low-Fidelity approach the CFD viscous corrected data will be used as nominal values.

Each aerodynamic database, based on the space-based approach (aerodynamics as function of flight conditions and vehicle's attitude and configuration) and build-up formulation, is complemented by a proper uncertainty model

Two different contributions to uncertainties are considered:

<u>Tolerances</u>: represent the confidence level on the aerodynamic coefficients in nominal conditions, and are mainly related to the accuracy of numerical and physical modelling used for the computations (grid, turbulence modelling, etc.) and the quality and accuracy of the experimental data (balance, pressure sensors, repeatability, etc.)

<u>Variations</u>: depend on the estimated possible differences between nominal and real flight conditions (both numerical and experimental), and are mainly based on the experience made in previous flights

Typically, being variations difficult to estimate in absence of previous flights, an uncertainty model contains only the tolerances and the variations are replaced with a safety factor applied on top of tolerances (i.e. 10%).

The final generic coefficient can be written as a summation of the nominal value and the uncertainty level as follows:

$$C_i\left(M,\ Re,\ \alpha,\ \beta, \delta_{flap}, \delta_{canard}, \delta_{bodyflap}, \delta_{rudder}\right) = C_{i_{nom}} \pm \Delta C_{i,unc}$$

2.3 Experimental Test Requirements

At the moment a first evaluation of the test requirements for the HTB vehicle has been done for what concerns the campaigns at INCAS Trisonic facility and VKI H3 wind tunnel. From Figure 3 we can see the preliminary Reynolds-Mach trajectory with the selected points for the measurements and the comparison with the values of wind tunnels.

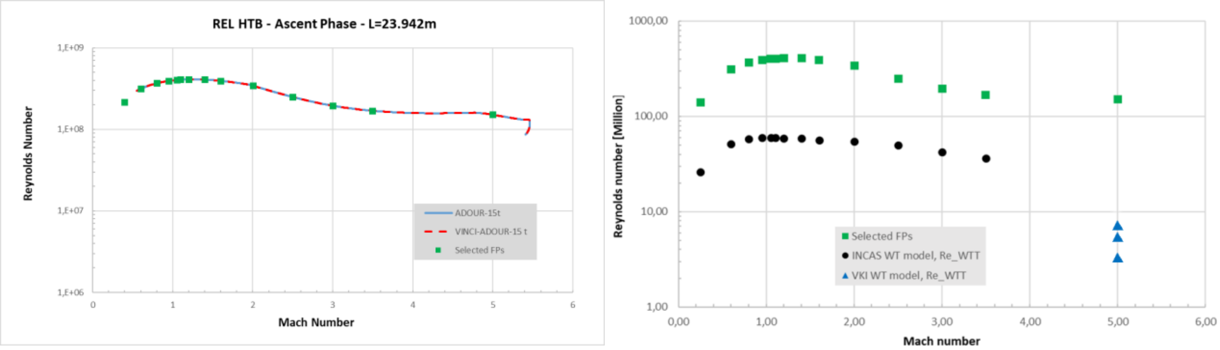

Figure 3 – Trajectory of HTB vehicle CS2 with selected points (left) and the comparison with wind tunnel points (right)

As can be seen from Figure 3-right an extrapolation to flight of experimental data is required due to the fact that the Reynolds number is lower in wind tunnel conditions. This can be done by means of high-fidelity CFD computations.
From this preliminary analysis we have two different wind tunnel models due to the different characteristics (test section dimension and Reynolds number). The lengths are respectively 0.87 m (INCAS) and 0.17-0.19 m (VKI-H3) while the real flight vehicle is about 24 m long.

3. Results

Several activities have been done for the development of all the databases foreseen in the More&Less project. Three main configurations are considered for the building of the holistic design environment of hypersonic civil aircraft: the Concorde-like Mach 2 vehicle CS1 (version A e B) for which only theoretical and numerical calculation are foreseen; the Hypersonic Test Bed by Reaction Engines Ltd. (CS2) and the MR5 (CS3) Mach 5 liquid hydrogen fuelled vehicles that are to be analyzed both experimentally and numerically. At time of writing of this note the activities are at the beginning phases and so only partial results are available and are reported in the following sections.

3.1 CS1 database

For this vehicle a wide range of Mach number and angle of attack is considered in order to obtain a complete aerodatabase for the clean configuration and a suitable number of flap deflections to study the trimmability and flyability for all flight conditions. A subset of sideslip angles is also foreseen for the lateral/directional stability verification. In the following the starting test matrices:

Table 1: Test Matrices

	Clean	
Mach	AoA	Run
[-]	[deg]	[#]
0.30	-5° -> 30°, step 5°	8
0.60	-5° -> 30°, step 5°	8
0.80	-5° -> 30°, step 5°	8
0.95	-5° -> 30°, step 5°	8
1.05	-5° -> 30°, step 5°	8
1.20	-5° -> 30°, step 5°	8
1.60	-5° -> 30°, step 5°	8
2.00	-5° -> 30°, step 5°	8

		Flap	
Mach	AoA	Delta Aileron	Run
[-]	[deg]	[deg]	[#]
0.30	0°	-25° -> 25°, step 10	7
0.60	0°	-25° -> 25°, step 10	7
0.80	0°	-25° -> 25°, step 10	7
0.95	0°	-25° -> 25°, step 10	7
1.05	0°	-25° -> 25°, step 10	7
1.20	0°	-25° -> 25°, step 10	7
1.60	0°	-25° -> 25°, step 10	7
2.00	0°	-25° -> 25°, step 10	7

		Sideslip	
Mach	AoA	Beta	Run
[-]	[deg]	[deg]	[#]
0.30	0°	0°, 3°, 6°	3
0.95	0°	0°, 3°, 6°	3
2.00	0°	0°, 3°, 6°	3

The clean configuration low fidelity data are obtained running on an unstructured grid of 2.1 million of cells for half configuration (longitudinal analysis) generated by means of the ANSYS-ICEMCFD-TETRA grid generator (Figure 4) and the use of the commercial code Ansys Fluent. From Figure 5 to Figure 7, where all predicted aerodynamic coefficients are reported, a different behaviour can be observed for subsonic and supersonic regimes. In particular the stall phenomenon starts at an angle of attach of 25 deg in subsonic regime while for the supersonic one a quasi linear trend seems to continue for higher angles of attack.

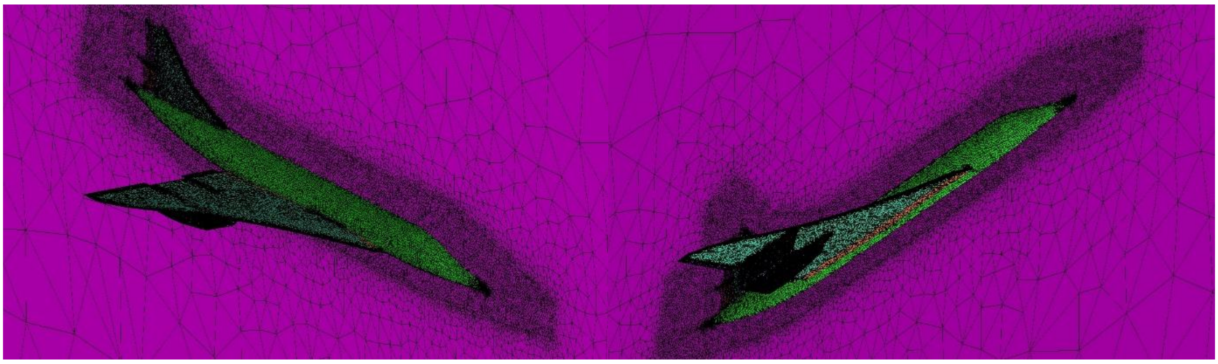

Figure 4: Unstructured Grid. Cells = 2.1 M.

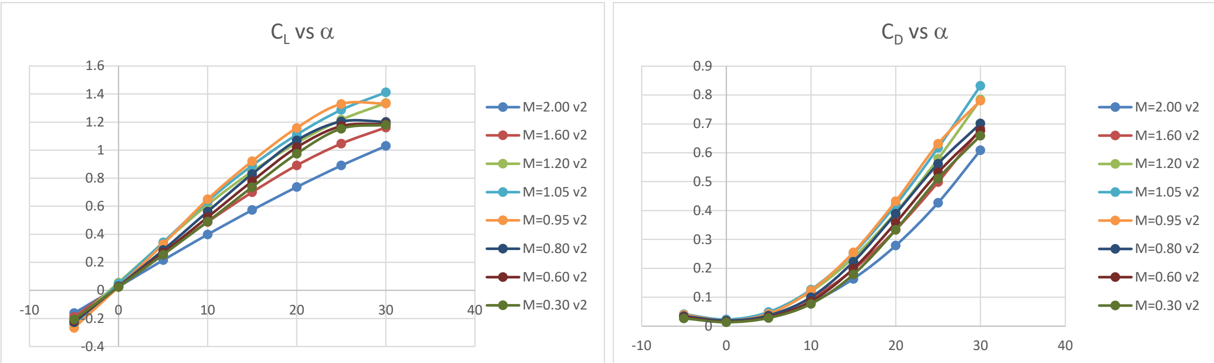

Figure 5: Lift and Drag versus Angle of Attack for all Mach numbers

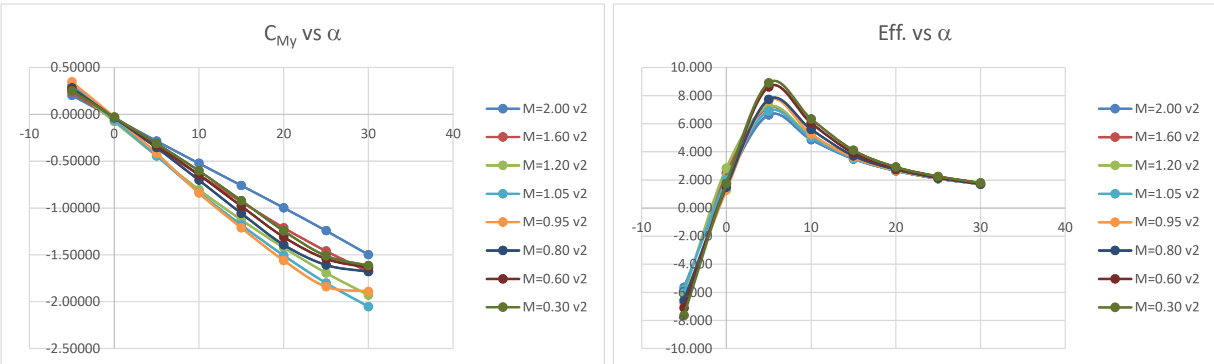

Figure 6: Pitching Moments and Aerodynamic Efficiency versus Angle of Attack for all Mach numbers

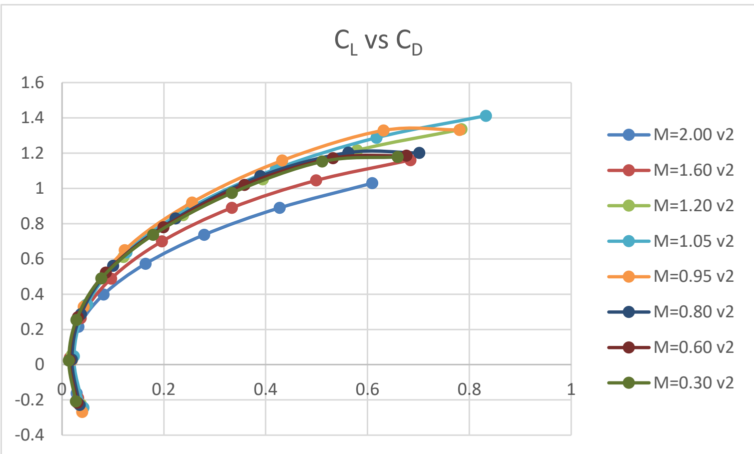

Figure 7: Polars for all Mach numbers

3.2 CS2 Database

For CS2 vehicle both wind tunnel tests and CFD simulations are foreseen in order to build a reliable aerodynamic database with suitable uncertainty levels. The experimental campaign is foreseen at INCAS (Mach = 0.4 -> 3.5) and VKI (M=0.5) wind tunnels on different models.
As already said, as reference geometry to be studied the Hypersonic Test Bed (HTB) vehicle concept currently under investigation by Reaction Engines Ltd. has been chosen. The HTB is intended to serve as a flying demonstrator or “test bed” for SABRE – the Synergetic Air-Breathing Rocket Engine – which is under development at Reaction Engines Ltd.. SABRE is set to revolutionise space access and hypersonic flight by enabling reusable, aircraft-like launch vehicles, and unique high-Mach propulsion technologies. The HTB also presents an important opportunity for commercial hypersonic research, serving as an experimental test platform for novel airframe and engine technologies.
The configuration of the HTB is not yet confirmed and several concepts are under consideration. Figure 8 illustrates the geometry of the vehicle currently being used for this study. As indicated, the vehicle features two propulsion systems:

- An experimental air-breathing engine, situated in a nacelle mounted on the upper fuselage
- A rocket engine, found housed inside the rear end of the fuselage

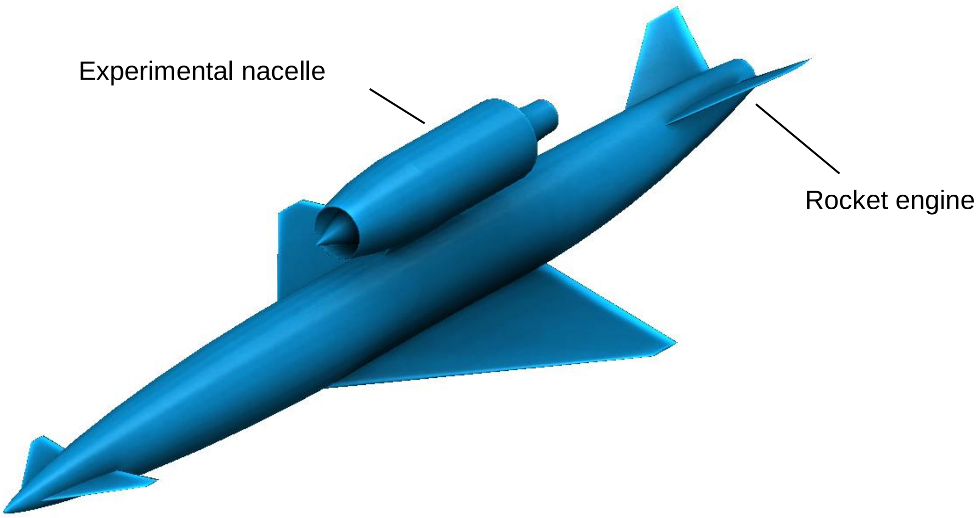

Figure 8: HTB geometry

The trajectory data was provided by REL and was used to generate the wind tunnel test matrix for CS-2 model (see Table 2).

Table 2: INCAS Test Matrix and Reynolds numbers.

	ADOUR 15t Concept trajectory											
Mach	0,40	0,60	0,80	0,95	1,05	1,10	1,20	1,40	1,60	2,00	2,50	3,50
Re (mllions)	TBD	315,23	368,41	393,28	403,60	407,37	411,11	408,01	394,30	343,85	250,28	169,23
Altitude (m)	TBD	694,72	2094,37	3208,91	3986,49	4323,44	5101,02	6708,03	8289,11	11295,76	14743,04	19382,62

In order to design the wind tunnel model is necessary to know the mechanical loads acting on it, and in particular the most loaded conditions in terms of dynamic pressure (Q) and attitude of the model (AoA, AoS).
Following the indications of INCAS, the most loaded condition from the test matrix is at Mach 2.5, P_0=3 bar, T_0=300K, Q=0.76817 bar, and there are three critical cases to be studied for their attitude:

1. AoA = 20 deg, AoS = 0 deg (for normal force and pitching moment),
2. AoA = 20 deg, AoS = 10 deg (rolling moment, yawing moment),
3. AoA = 0 deg, AoS = 10 deg (nacelle and pylon will be exposed laterally which means higher loads on these parts).

Note that the most loaded condition in the test matrix was considered to be at Mach 2.5, given the fact that yields the largest dynamic pressure. The critical case will be updated if the CFD will show another regime to produce higher aerodynamic loads.

The reference geometrical properties are:

Flight full configuration	INCAS WT (1:28)
L_{ref} = 24.534 m	L_{ref} = 0.876214 m
S_{ref} = 40.7751 m^2	S_{ref} = 0.052009 m^2
Moment Reference Point = Nosetip	

The coefficients for the forces and moments are normalized as:

$$C_{Force} = \frac{Force}{Q * S_{ref}}$$

$$C_{Moment} = \frac{Moment}{Q * S_{ref} * L_{ref}}$$

The reference system is the one used for CFD simulations as shown in Figure 9, for which:

- The origin is located at the nosetip,
- The x-axis is directed from nose to base,
- The y-axis is directed toward the right (as right wing),
- The z-axis is such to form a right-handed reference system (from bottom to up).

In order to use the classical aeronautical reference system (see Figure 10) it must be changed the direction of x and z axes, and also the signs of rolling and yawing moments (C_l, C_n). The angle of sideslip (AoS) is positive if the wind comes from the right of the vehicle, thus meaning that for a positive AoS the y-component of velocity is negative. In the following the formulas for the three velocity components:

$$u = \cos\alpha\cos\beta$$
$$v = -\sin\beta$$
$$w = \sin\alpha\cos\beta$$

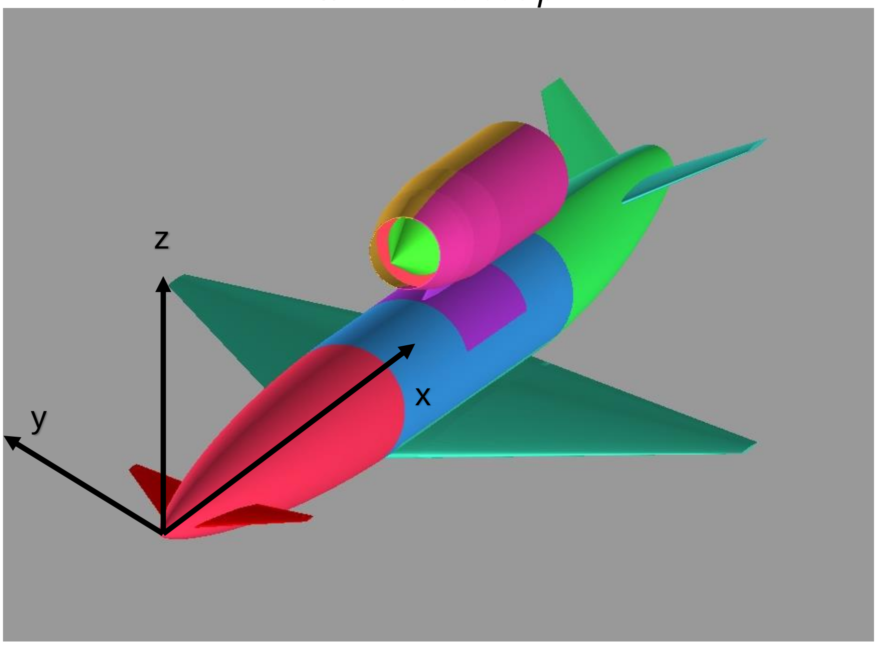

Figure 9: CS-2. CFD Reference System

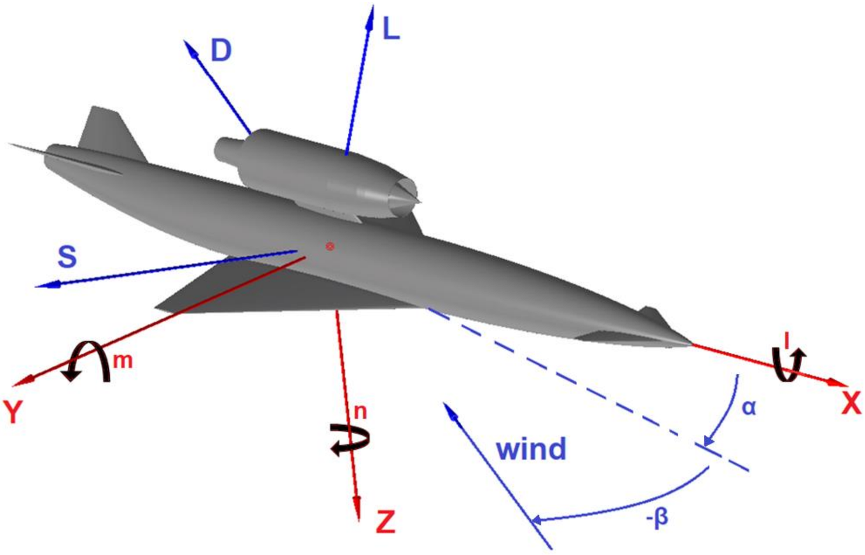

Figure 10: CS-2. Aeronautical Body and Wind Reference Systems

An unstructured Eulerian grid of about 7.5 million of cells on the full-body has been generated by means of ICEMCFD-TETRA (Figure 11) software, and the CFD simulations have been obtained by using ANSYS-FLUENT code in the hypothesis of inviscid flow.

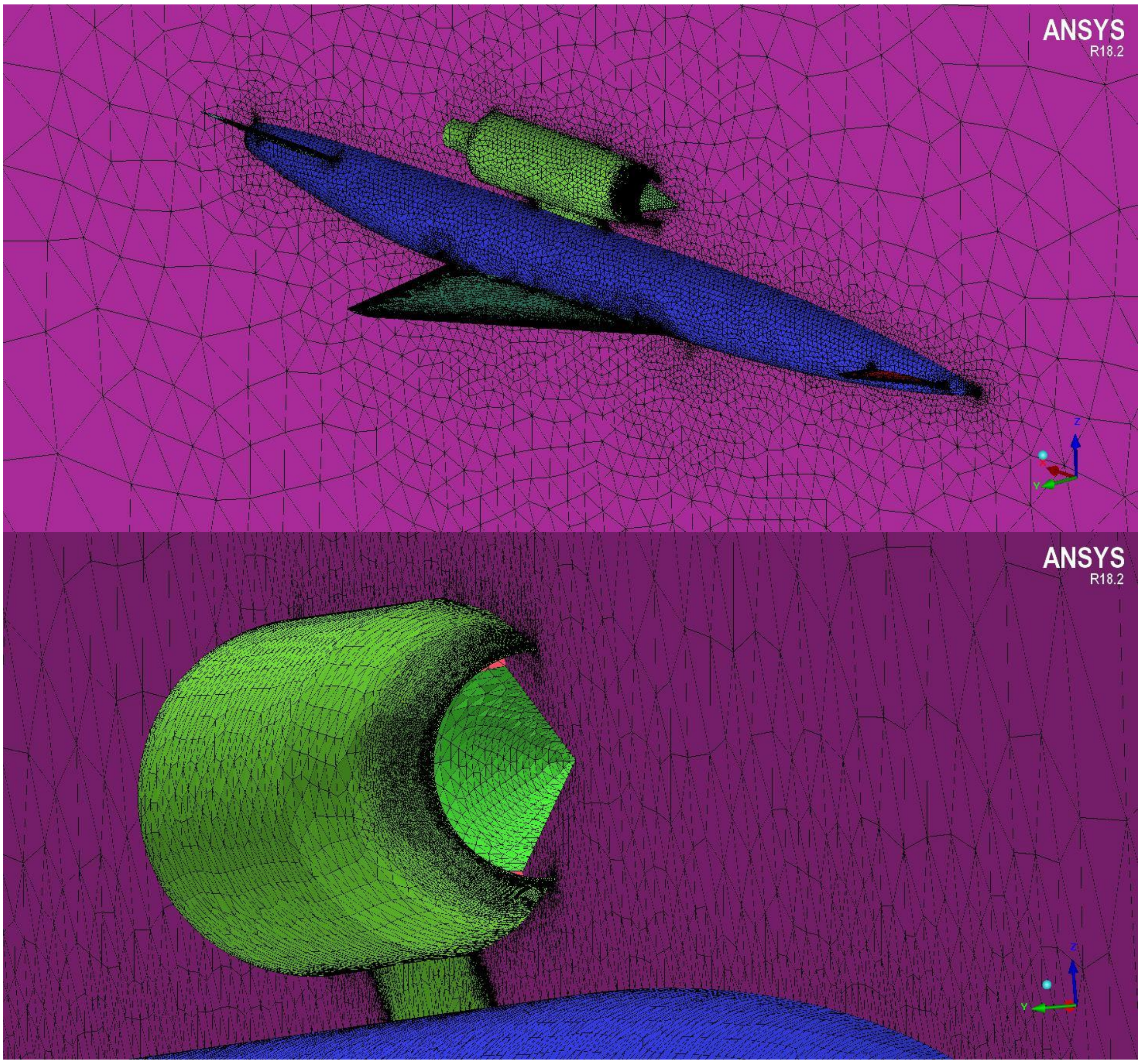

Figure 11: CS-2. Eulerian Grid. 7.5 million cells on full-body

In the following figures (Figure 12 and Figure 13) the Mach number contours at an angle of attack of 20° are reported. Large expansion and recompression zones are predicted over the wing and fuselage. It can be noted as the shock in front of the inlet spike is well swallowed by the nacelle and the shock of the nacelle impinges over the top fuselage creating an overpressure zone (Figure 14).

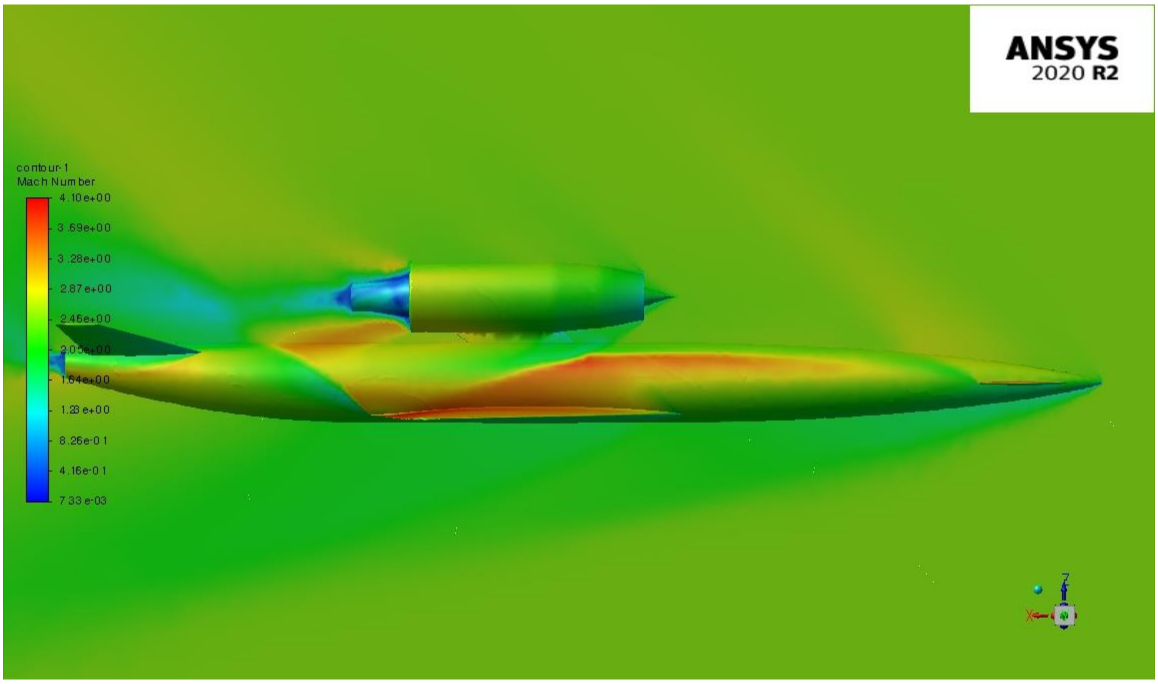

Figure 12: CS-2, Mach number contours at M=2.5, AoA=20°, AoS=0°. Side view.

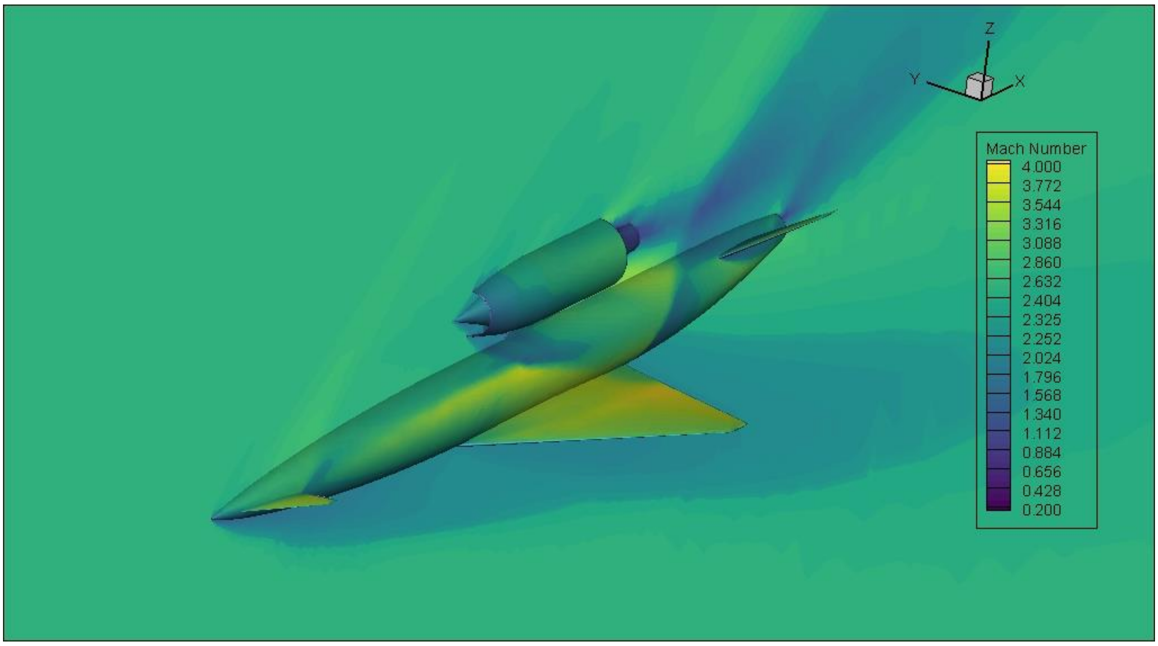

Figure 13: CS-2, Mach number contours at M=2.5, AoA=20°, AoS=0°. Isometric view.

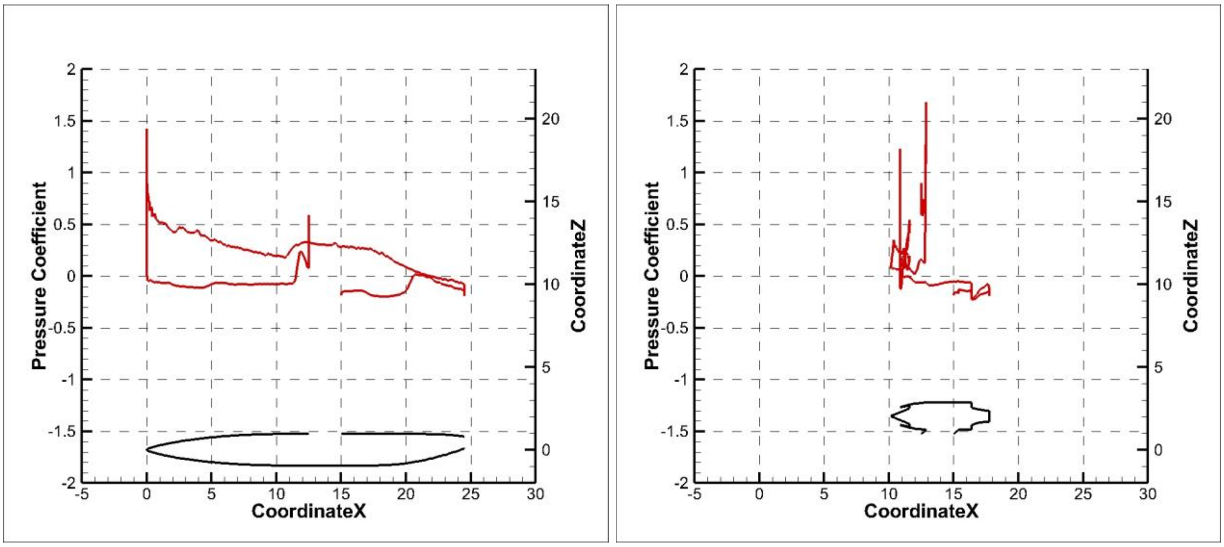

Figure 14: CS-2. Cp distribution at Y=0m. Fuselage (left) and Nacelle (right)

The INCAS wind tunnel model is mounted on a supporting sting and is composed of several parts (indicated by different colours) as depicted in Figure 15, and for each of these parts the mechanical loads in the critical conditions must be known, this in such a way to support the model design and fix a safety factor for the model structure.

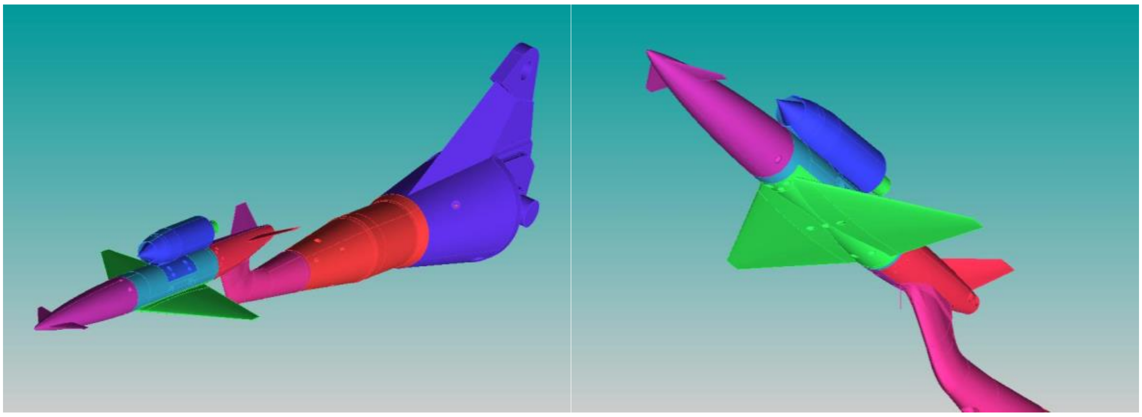

Figure 15: CS-2 wind tunnel model

The aerodynamic coefficients are extracted for the full model configuration (Table 3) and for all the several parts the model is composed of.

Table 3: Full model coefficients

full			Pitch	Roll	yaw	Normal	Axial	Side
Mach	Alpha	Beta	***Cm (ext)***	***Cl (ext)***	***Cn (ext)***	***Cz***	***Cx***	***Cy***
2.50	20	0	-0.36198	0.00000	0.00000	0.69899	0.027549	0.000000
2.50	0	10	0.01200	0.00167	-0.08774	-0.02076	0.032775	-0.177494
2.50	20	10	-0.36281	0.00666	-0.07934	0.69694	0.026021	-0.151077

4. Conclusions

This paper dealt with the development and integration of increasing-fidelity aerodynamic modelling approaches in the conceptual design of supersonic and hypersonic cruisers. The adopted methodology foresaw the development of aerodynamic aerodatabases by means of incremental steps starting from simplified methods up to very reliable data based on high fidelity CFD simulations and experimental measurements with associated confidence levels. A build-up approach is adopted from the clean external configuration up to the complete configuration, including Control Surfaces effects and, if any, the Propulsion Systems Elements. Several supersonic/hypersonic configurations have been considered in the development of such databases in order to build a holistic design framework for future high-speed civil aircraft. In this paper some preliminary results are reported of ongoing activities.

5. Copyright Statement

Acknowledgment

This work has been carried out within the frame of “MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation” (MORE&LESS) project. This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 101006856.

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