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Preliminary Numerical Aerodatabase of VEGA C Launcher

Pietro Roncioni [(1)], Pier Luigi Vitagliano [(1)], Fabio Paglia [(2)] , Daniele Schiariti [(2)] , Claudio Milana [(3)]
[(1)] CIRA (Italian Aerospace Research Centre), via Maiorise, 81043 Capua (CE), Italy
[(2)] AVIO Spa, via Ariana km 5,2 – 00034 Colleferro (Rome), Italy
[(3)] ELV SpA, via degli esplosivi 1 - Colleferro (Rome), Italy, 00034

Abstract

In the framework of VECEP Program (Vega Consolidation and Evolution Preparation) whose target is the development of the VEGA C Launcher, characterized by higher capabilities in terms of payloads and propulsion power, CIRA has been assigned by AVIO of the building of the aerodynamic database (ADB). This is foreseen to be obtained by means of both wind tunnel tests and CFD simulations that coupled with suitable aerodynamic and uncertainties models will give the aerodynamic coefficients in the ranges of required Mach and attitude and along the given trajectory. The present report describes some preliminary CFD results concerning the clean configuration in the complete flow regime and the procedure adopted to build the final ADB.

1. Introduction

One of the main tasks within the framework of VECEP Program is the development of the launcher VEGA C aerodynamic database (ADB). The ADB, coupled with a suitable uncertainties model, is of paramount importance being the input for flight mechanics analysis and structural calculations; it will be obtained by means of both wind tunnel tests and numerical calculations.

Wind tunnel tests will be carried out in the critical transonic and low supersonic regimes, while CFD simulations will cover all the Mach number range of the atmospheric flight, with the objective of generating the database in the hypersonic regime and supporting the extrapolation to flight of wind tunnel data in the other flow regimes.

The final ADB will be a combination of experimental data and numerical results together with uncertainties values and dispersion errors in order to produce a confidence level model coupled to the nominal values of the aerodynamic coefficients.

A preliminary version of the aerodatabase, to be issued before the end of the wind tunnel test campaign, will be obtained by means of numerical data only. The clean configuration of the launcher will be considered in order to evaluate the global aerodynamic coefficients as functions of Mach number and incidence angle. The effect of the plume at the nozzle exit, both for 4 stages and 3 stages configurations, will be taken into account as a perfect gas. Some preliminary CFD results and the procedure adopted to produce the final ADB are described in the present report.

2. Program and Vehicle Description

The VEga Consolidation and Evolution Programme (VECEP) has entered into force on 21 November 2012, following subscriptions made by participating States at the occasion of the ESA Council meeting at ministerial level in Naples. Following the Scenarios Expert Group sessions hold during summer 2014, a new orientation in the Ariane programmes has been defined, which has impacted the Vega evolution scenario. Indeed it has been decided to develop a common SRM (hereafter named P120C) to be used both as Vega 1st stage SRM and strap-on boosters for the Ariane 6-2 (2 boosters) and Ariane 6-4 (4 boosters) PHH configurations. Furthermore, this change on the 1st stage propulsion has led to suggest the substitution of the Zefiro 23 with a new 2nd stage SRM - the Zefiro 40 - which provides a better staging of the Vega launcher. The new baseline architecture for Vega C has become then: P120C/Z40/Z9/AVUM+.
The Vega C launcher will increase by at least 700 kg the nominal Vega performance on its reference mission and provide an enhanced service at a recurring cost not exceeding the Vega second batch procurement cost. More specifically, the gain in performance – w.r.t the current Vega – shall at least balance/compensate the losses related to the applicable safety constrains (e.g. FSOA, Space Debris Policy) and provide additional margin for complex missions requiring significant flexibility in the flight strategy, without any increase of the recurring costs. Options to enlarge the potential market by providing cost efficient launch service solution will be studied in particular for new

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strategy to orbit, using electric propulsion for servicing MEO or GEO Small Satellite market, and new solutions for accommodation of smallsats, in a multiple launch configuration.

3. Aero Data Base Building

Two ranges of Mach are considered: M=0.5 – 3.5 (subsonic-transonic-supersonic) for which both WT and CFD data are (will be) available and M=3.5 – 7.0 (hypersonic) where only CFD data are used for building of the aerodatabase. This approach is due to the choice of focusing the experimental campaign, that is being conducted at INCAS facility in Romania, on a restricted range of Mach number, mainly in order to contain the experimental costs. The results of previous test campaigns (VEGA in 2003) will be used in order to make up for this lack of data.

The aerodatabase is obtained by means of a build-up approach used for both the coefficients and the uncertainties levels. The output of the aero data package is constituted by the six aerodynamic coefficients and the pressure distribution: CL, CD, CS, CMx, CMy, CMz, p=p(surface). The independent variables are: Mach number, angle of attach α, Reynolds number Rey, roll angle ϕ, and the nozzle angle.
Each aerodynamic contribution is a summation of several contributions and each of this contribution is function of one or more variables.
In particular we have for each Mach range the following formulas:
Sub-transonic-supersonic range (M = 0.5 – 3.5)

$C_{i,N}^{FL}(\alpha, M, Re, \varphi, Noz) =$	**Nominal generic coefficient in flight cond.**
$C_{i,WT}(\alpha, M) +$	*Clean contr.*
$\Delta C_{i,WT}^{Prot}(\alpha, M, \varphi) +$	*Protusion contr.*
$\Delta C_{i,base}^{CFD}(\alpha, M) +$	*Base contribution (CFD)*
$\Delta C_{i,Noz}^{CFD}(\alpha, M, Noz) +$	*Canted Nozzle contribution (CFD)*
$\Delta C_{i,Re}^{CFD}\ (\alpha, M, Re)$	*Re effect (Extrapolation to flight)*

Hypersonic range (M = 3-5 – 7.0)

$C_{i,N}^{FL}(\alpha, M, Re, \varphi, Noz) =$	**Nominal generic coefficient in flight cond.**
$C_{i,CFD}(\alpha, M) +$	*Clean contr. Includind base*
$\Delta C_{i,CFD}^{Prot}(\alpha, M, \varphi) +$	*Protusion contrribution*
$\Delta C_{i,CFD}^{Noz}(\alpha, M, Noz)$	*Canted Nozzle contribution*

The final Coefficient is the summation of the above nominal value and the uncertainty contribution:

$C_i^{FL}(\alpha, M, Re, \varphi, Noz) =$	**Generic coefficient in flight cond.**
$C_{i,N}^{FL}(\alpha, M, Re, \varphi, Noz) +$	Nominal generic coefficient in flight cond.
$\Delta C_{i,UNC}(\alpha, M, Re, \varphi, Noz)$	Uncertainty contribution

Where for sub-transonic-supersonic flow regimes we have:

$\Delta C_{i,UNC} =$	
$\Delta C_{i,UNC}^{WT} +$	Wind Tunnel Uncertainty contribution
$\Delta C_{i,UNC}^{CFD}$	CFD-ETF Uncertainty contribution

And for hypersonic flow regime:

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$\Delta C_{i,UNC} =$	
$\Delta C_{i,UNC}^{WTvsCFD} +$	Uncertainty due to unavailability of Exp data
$\Delta C_{i,UNC}^{CFD}$	CFD Uncertainty contribution

The uncertainty reported in the above formulation takes into account two kinds of contribution:
uncertainties:
- WT balance
- WT corrections
- CFD-GRID
- CFD-Modeling
- CFD-NoExp (unavailability of experimental data)

dispersions:
- WT repeatibility
- difference of WT model and/or testing wrt flight conditions
- difference of CFD model and/or running wrt flight conditions

The CFD-NoExp is an uncertainty term that takes into account for the lack of experimental data in the hypersonic range and for some parts in the transonic range (no base drag measurements and no measurements with canted nozzle).

3.2 CFD Methodology

The following CIRA in-house codes have been used, depending on the Mach regime.
ZEN (Zonal Euler Navier-stokes) for STS range (SubTransSuper sonic range)
ZEN is a multiblock structured flow solver for steady and unsteady RANS equations, which has been developed at CIRA for more than two decades [4], [5], [6], [9], [10], [13]. It is based upon cell centered, finite volumes formulation, with central schemes. Convergence toward steady state is achieved by explicit multi-stages Runge-Kutta schemes, with acceleration techniques like local time stepping, residual averaging and multigrid [7]. Several turbulence models are available; all solutions in the present work were computed using the k-ω TNT two equations model [8]. Condition of free transition from laminar to turbulent flow was selected. ZEN was used in the past for CFD analysis of VEGA configuration both in flight and in wind tunnel conditions ([11], [12]).
Comparisons with wind tunnel experiments carried out in the year 2004 on a 1:30 scaled model (3 stages and 4 stages configurations, with and without protrusions, including engine jet simulation) at FOI (Swedish Defense Research Agency) and at DNW SST (German Dutch Wind Tunnel) and on two 1:40 scaled models at DLR Hypersonic facility H2K in Koeln, demonstrated good agreement in the complete range of Mach and Reynolds numbers considered.
NExT (Numerical Experimental Tool) for Hypersonic range.
The CIRA code NExT ([14]) solves, on a multi-block structured grid, the Reynolds Averaged Navier Stokes equations in a density-based approach.
It allows the treatment of a wide range of compressible fluid dynamics problems for both aerothermodynamic and combustion applications. The Chemkin® input interface permits to treat different mixtures of reacting gases, specifying mixture composition and chemical kinetic scheme. A thermal database contains the transport coefficients and the thermodynamics data for each species.
Specific thermodynamics and transport models are available for aerothermodynamic applications.
The fluid can be treated as a mixture of gases in thermo-chemical non equilibrium. The energy exchange between vibrational and translational modes (TV) is modelled with the classical Landau-Teller non-equilibrium equation, with average relaxation times taken from the Millikan-White theory modified by Park. For what concerns transport coefficient, the species viscosity, and thermal conductivity, are calculated by means of the Eucken law whereas, the mixture viscosity and thermal conductivity are calculated by using the semi-empirical Wilke formulas. The diffusion coefficients are computed through a sum rule of the binary diffusivities for each couple of species. With respect to the numerical formulation, conservation equations are written in integral form, and discretized with a finite volume, cell centred, technique. Eulerian fluxes are computed with a Flux Difference Splitting (FDS) upwind method. Second order formulation is obtained by means of an Essentially Non Oscillatory (ENO) reconstruction of interface value. Viscous fluxes are computed with a classical centred scheme.
A two-equation k-ε turbulence modelling is used for eddy viscosity calculation while laminar-to-turbulence transition is imposed across surface lines (i.e. a transition front). Some versions of the two-equation k-ε model are available:

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standard, RNG and with compressibility effects correction for the present high speed turbulent flows simulations ([15]).

3. Numerical Results

The test matrix of all CFD simulations is reported in Table 1. The aim of the numerical simulations is both for extrapolations to flight of experimental measurements and for the building of a preliminary Aerodatabase based on CFD simulations only. Two configurations have been simulated, the 4-stage (Figure 1, above) flying up to about Mach 6 and the 3-stage (Figure 1, below) flying from Mach 6 to higher values. Mach 7 is the upper limit for the ADB. The 4-stage configuration has been simulated with two different nozzle positions: 0 and 6 degrees (Figure 3)
In the range of Mach between 0.5 and 3.5 experimental data will be available and so the CFD data will be used for the extrapolation to flight and for estimation of the aerodynamic contributions not measured in wind tunnels (forces on base and nozzle). For higher Mach number only CFD simulations will be available to build the ADB. In this paper a preliminary version of the aerodatabase is reported, based on the nominal values of 4-stage configuration CFD simulations.

Table 1: Clean Configuration Test Matrix. 4 stage at flight Reynolds conditions

Regime	**Mach** [-]	**Reynolds** [-]	**AoA** [deg]	**Body grid**	**Conf.**	**Nozzle** [deg]
Sub-Transonic	0.50	Flight	0°,5°,10°	Half	baseline	0°
	0.80	Flight	0°,5°,10°	Half	baseline	0°
	0.85	Flight	0°,5°,10°	Half	baseline	0°
	0.95	Flight	0°,5°,10°	Half	baseline	0°
	1.05	Flight	0°,5°,10°	Half	baseline	0°
	1.10	Flight	0°,5°,10°	Half	baseline	0°
	1.20	Flight	0°,5°,10°	Half	baseline	0°
Supersonic	1.70	Flight	0°,5°,10°	Half	baseline	0°
	*1.70**	*Flight*	*0°,5°,10°*	*Half*	*baseline*	*6°*
	2.00	Flight	0°,5°,10°	Half	baseline	0°
	*2.00**	*Flight*	*0°,5°,10°*	*Half*	*baseline*	*6°*
	3.50	Flight	0°,5°,10°	Half	baseline	0°
Hypersonic	5.00	Flight	0°,5°,10°	Half	baseline	0°
	5.44	Flight	0°,5°,10°	Half	baseline	0°
	5.91	Flight	0°,5°,10°	Half	baseline	0°

* The canted nozzle run are used for local load calculation

Input for the present work, provided by AVIO, are: the geometry, the nominal trajectory, and the nozzle plume condition for both 4-stage and 3-stage configurations. The reference quantities for the calculations of the aerodynamic conditions are the diameter of the first stage (L_{ref}) and the relevant surface (S_{ref}) and Moment Reference Centre is the launcher nose. Figure 3 shows details of base region for the two attitudes of the nozzle (zero and six degrees).

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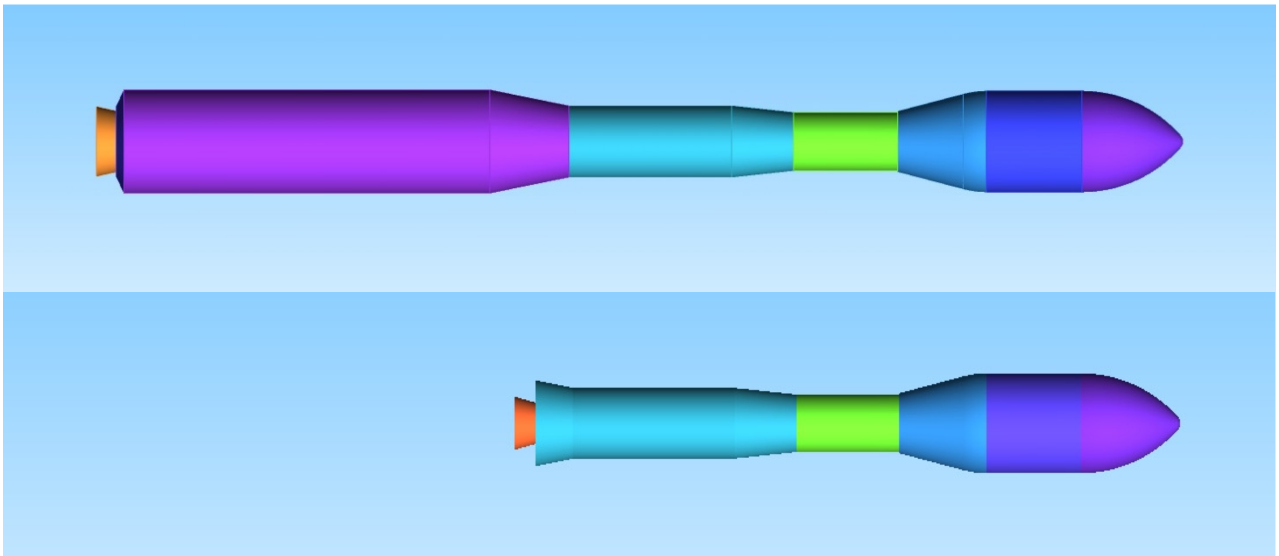

Figure 1: 4-stage and 3-stage version of VEGA C launcher. Clean configuration.

The adopted reference axis systems for the calculation of the aerodynamic coefficients are reported in Figure 2 and follows the classical aeronautical convention. In particular for the body axis reference system we have: origin on launcher base; x axis along model centreline, positive towards the nose; y axis normal to x in the horizontal plane, positive right; z axis normal to x and y, positive following right – hand rule. The wind axis reference system is obtained by rotation of the angle of attack around the yb axis. The moments are positive if counter-clockwise (as in figure) while for the forces we have: CA=-CXb, CN=-CZb; CD=-CXa, CL=-CZa, CS=CYb=CYa.

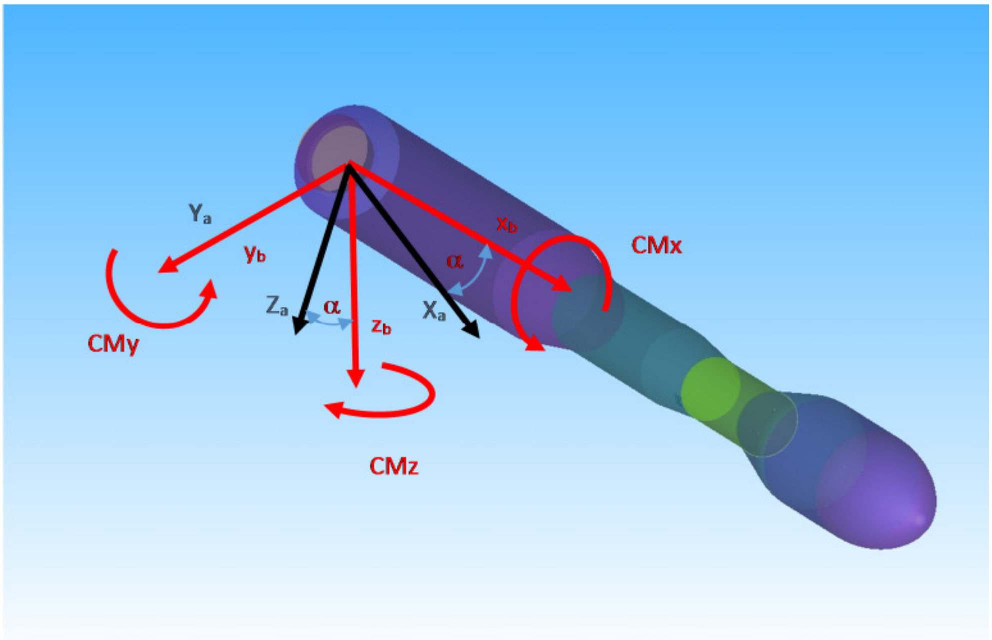

Figure 2: Body and wind reference system.

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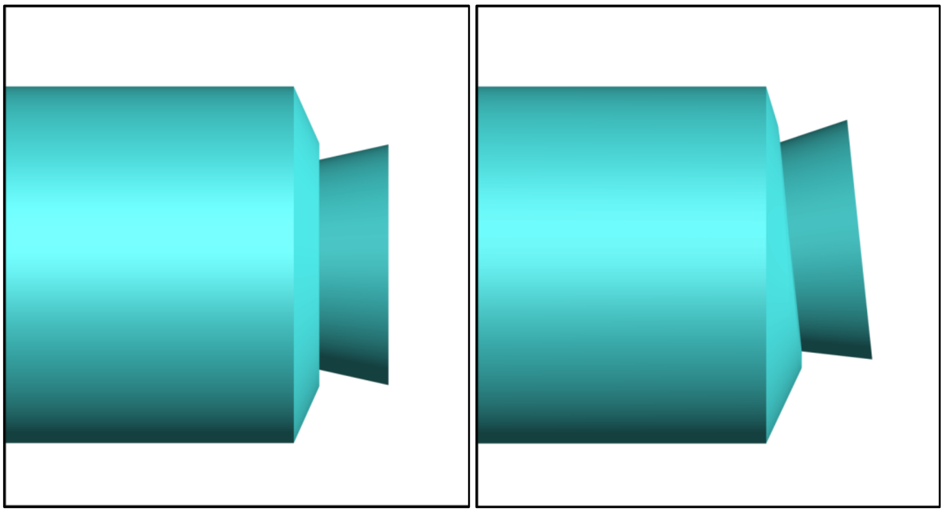

Figure 3: 4-stage clean geometry used for CFD computations. Detail of nozzle region. Left: reference nozzle. Right: 6 degrees canted nozzle

Several grids have been used in order to perform the present simulations: 4-stage for sub-transonic (free stream Mach from 0.5 to 1.2), 4 stage for supersonic ($M\infty$ from 1.7 to 2.0), clean and 6 degrees canted nozzle, 4-stage for hypersonic (Mach 3.5 – 6.0) and 3-stage for hypersonic (Mach = 4.0 – 7.0).
The Grid characteristics are reported in Table 7 3.

Table 2: Main characteristics of the Grids

	4Stage sub-trans	**4Stage supersonic**	**4Stage supersonic canted**	**4Stage hyper**	**3Stage hyper**
Levels	3	3	3	3	3
Cells (million)	13.3	13.3	13.3	4.1	3.5
Blocks	13	13	13	77	65

In the following figures, some pictures of the grids are reported.

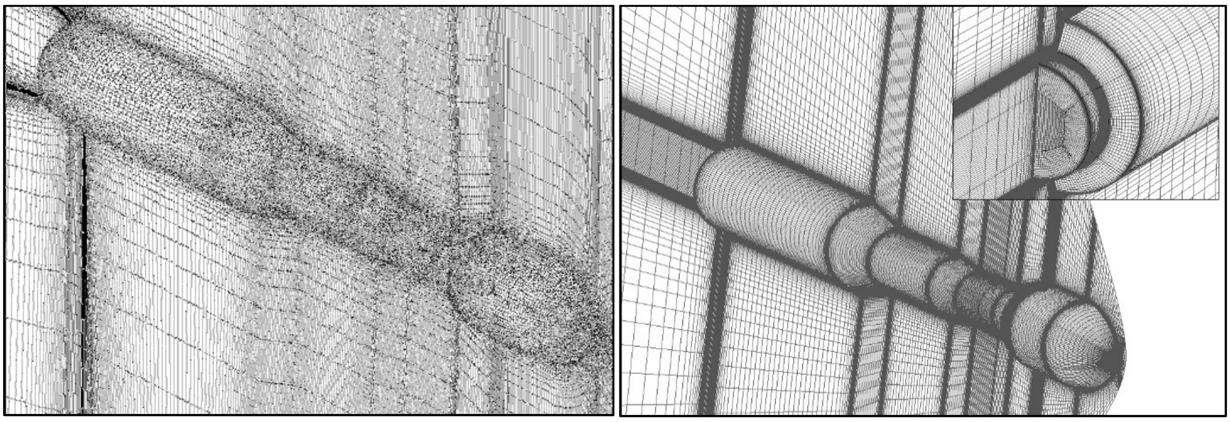

Figure 4: VECEP Grids for Transonic (left) and Hypersonic (right) ranges.

The grid sensitivity analysis has been conducted in order to be sure of using a proper number of points. The case of the 4S-hyper configuration at Mach = 5.00, α=5° is depicted in the following Figure 5. Three grid levels have been considered, the lower levels being obtained by halving the amount of cells of the finer grid in each direction. The trend of pitching moment coefficient and centre of pressure (X_{cp}) is reported versus the parameter h that is representative of the average value of the grid dimension: h= $1/(\mathrm{Cells})^{1/3}$

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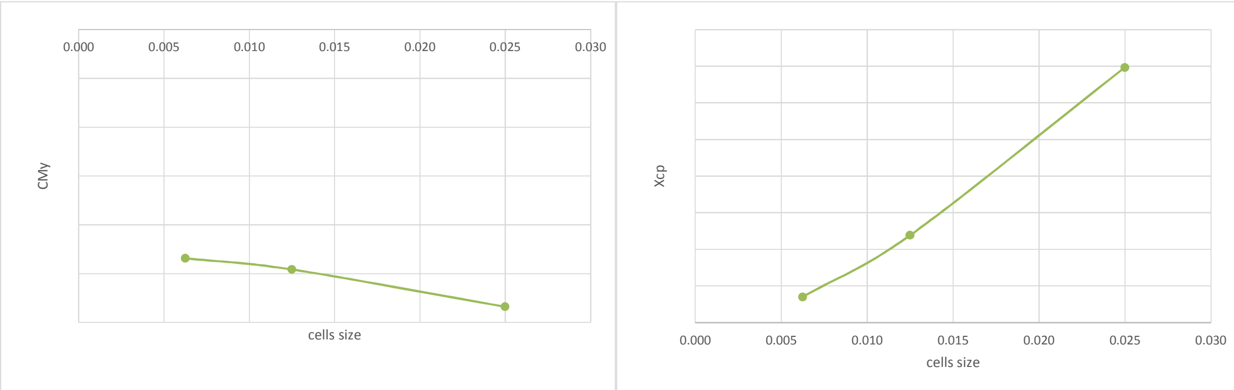

Figure 5: Grid sensitivity analysis for Hypersonic 4-stage configuration: Pitching Moment and Centre of Pressure.

In the following figures some contours plot are reported for Mach 0.95 and 3.50. It is interesting to remark, for the Mach=3.5 case, the position of the shock wave in the boat tail region. This could give a possible buffeting phenomenon due to the fluidynamic instability of this position. At the moment is not possible to have this information because the present simulations are carried out in steady-state hypothesis.

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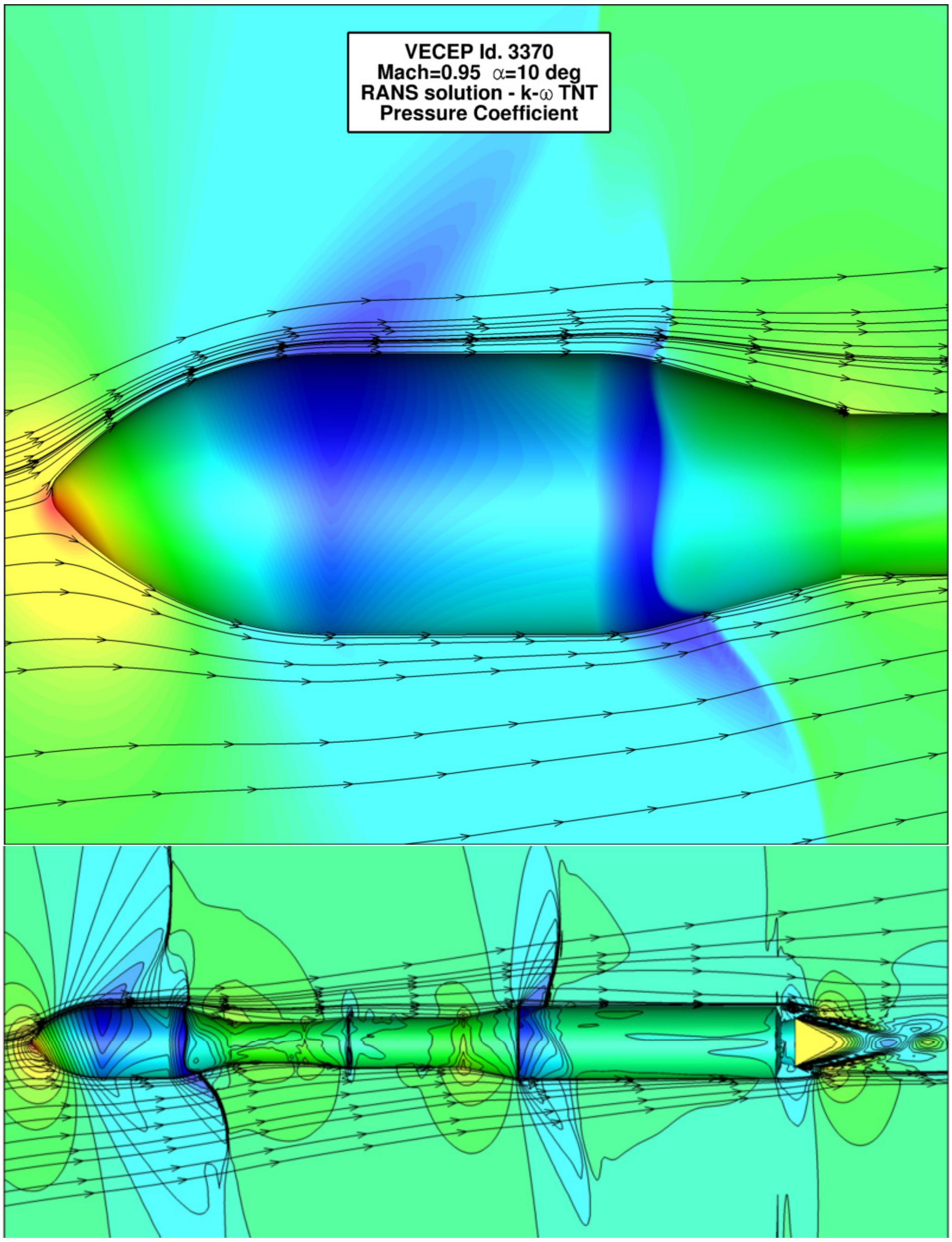

Figure 6: Pressure contours at M=0.95.

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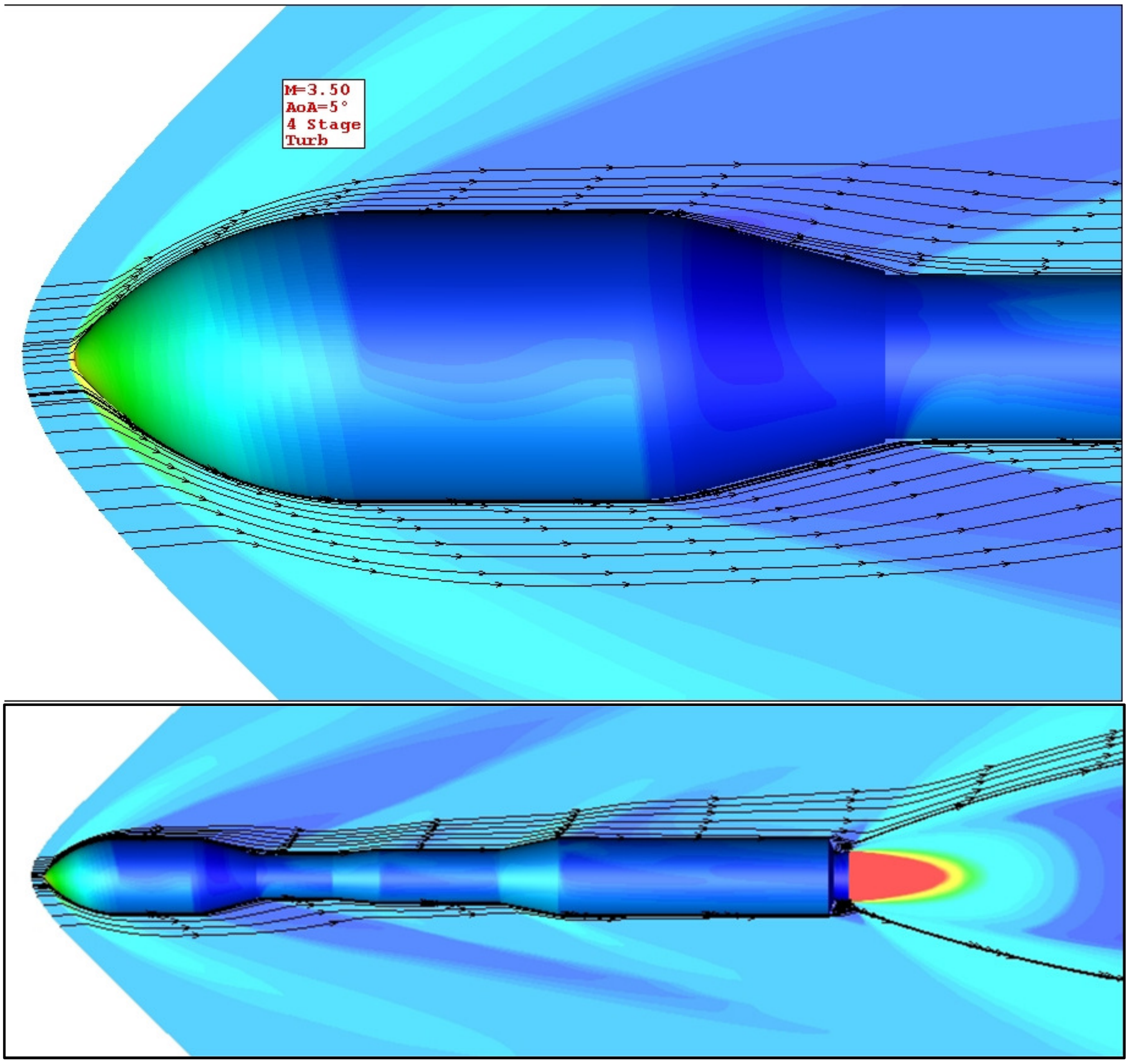

Figure 7: Pressure contours at M=3.50.

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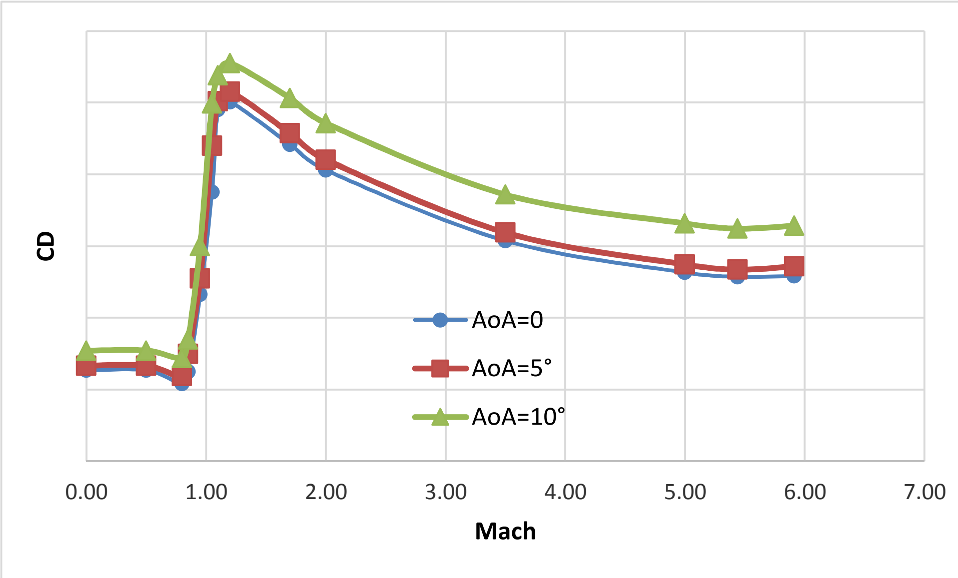

Figure 8: Drag coefficient vs Mach. Full range of Mach

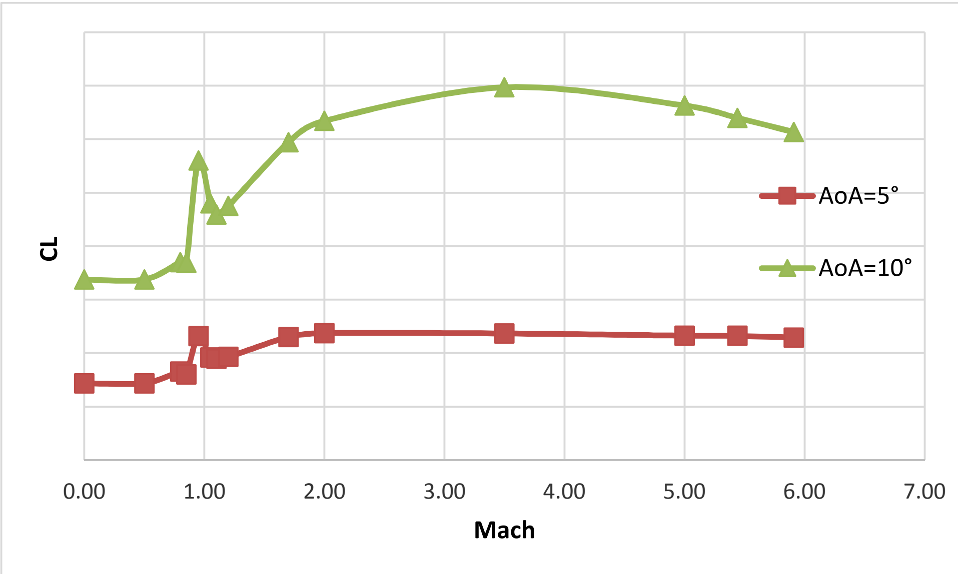

Figure 9: Lift coefficient vs Mach. Full range of Mach

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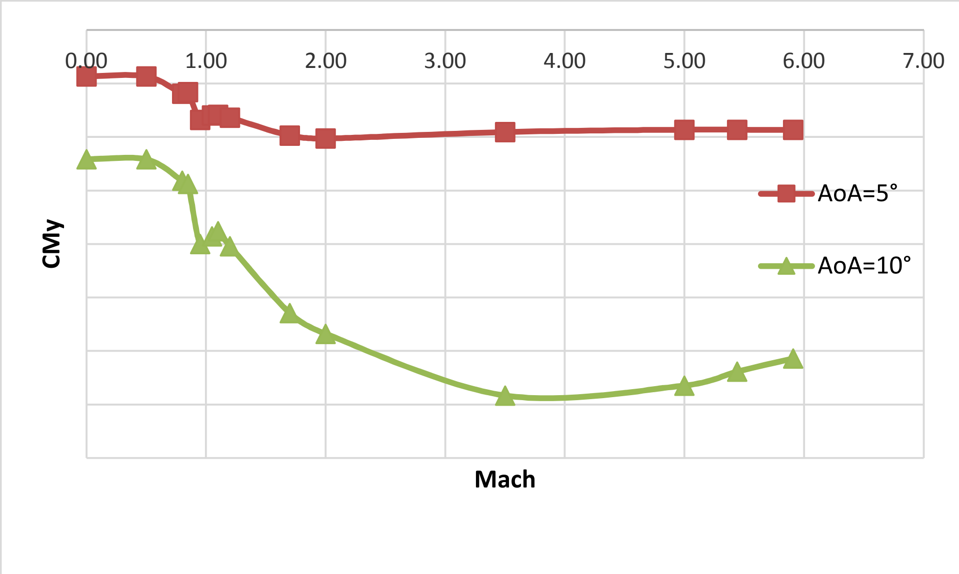

Figure 10: Pitching moment coefficient vs Mach. Full range of Mach

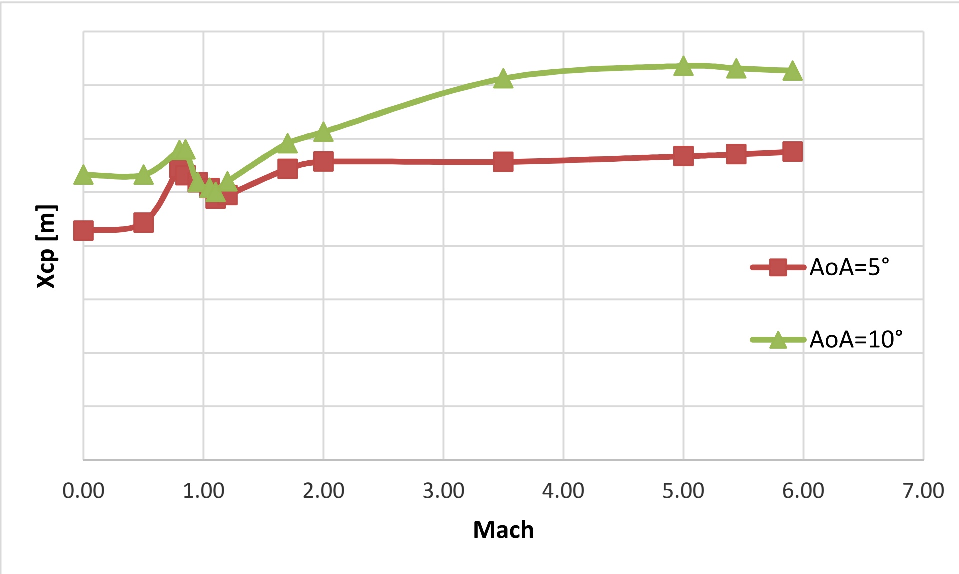

Figure 11: Centre of pressure vs Mach. Full range of Mach

The behaviour of the main aerodynamic coefficients are reported from Figure 8 to Figure 11. After the transonic range, where typical oscillations can be observed, a flat region arises after Mach 2.0 at the angle of attack of five for lift, pitching moment and centre of pressure. A non linear behaviour is exhibited versus the angle of attack at all Mach numbers. At ten degrees of angle of attack no flat region is reached up to mach six for all the coefficients. This behaviour can be partially explained by the presence of a non constant plume of the first stage solid rocket.

3. Conclusions

In this report a preliminary database of the VEGA C Launcher has been reported based on numerical simulations, together with the procedure adopted to produce the final aerodynamic database.
The simulations concerned the clean configuration (without protrusions) both in sub-transonic and hypersonic ranges. The canted nozzle (6 degrees) configuration has also been considered in order to give mechanical loads on the nozzle at free stream Mach 1.7 and 2.0. Nominal values of the main aerodynamic coefficients (Drag, Lift and

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Pitching Moment coefficients) are provided.The present database has to be considered as preliminary, since the final one will be based mainly on the experimental test campaign.

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