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# Aerodynamic analysis of a high-speed aircraft from hypersonic down to subsonic speeds

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**Abstract.** Unmanned flying-test bed aircraft are fundamental to experimentally prove and validate next generation high-speed technologies, such as aeroshape design, thermal protection material and strategy; flight mechanics and guidance-navigation and control. During the test, the aircraft will encounter realistic flight conditions to assess accuracy of new design choices and solutions. In this framework, the paper focuses on the longitudinal aerodynamic analysis of an experimental aircraft, with a spatuled body aeroshape, from subsonic up to hypersonic speeds. Computational flowfield analyses are carried out at several angles of attack ranging from 0 to 15 deg and for Mach numbers from 0.1 to 7. Results are detailed reported and discussed in the paper.

## Introduction

Advancements in high-speed technologies strongly rely on the development of flying-test beds [1].

In fact, performing flight and Wind Tunnel (WT) test campaigns represent the only and ultimate proof to demonstrate the technical feasibility of next generation high-speed aircraft (HAS) concepts and technologies [2], [3]. In this framework, the paper reports on the longitudinal aerodynamics of the Vanvitelli-one (V-one) flying test bed, shown in Figure 1 [4],[5].

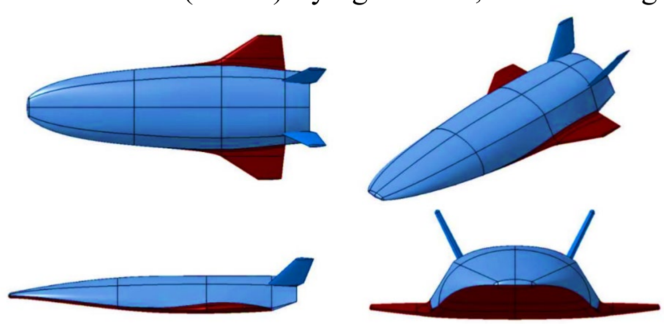

*Figure 1 – Four views of the concept aeroshape [4], [5].*

The V-one aircraft aims to provide a research platform suitable for a step-by-step increase of the readiness level of several enabling hypersonic technologies by means of both WT and in-flight experimentations. The V-one aeroshape features a classical lifting-body aeroshape which embodies all the features of an operational HSA, such as a low aspect ratio double-delta wing, two full movable vertical stabilizers in butterfly configuration, a spatuled fuselage forebody, characterized by a rounded off two-dimensional leading edge, mated on top of the wing. The wing flap, which must be actuated as elevon and aileron, is shown in purple in Figure 2 along with the complete moving fins (ruddervators) in green. The ruddervators pivot point is located at 50% of the root chord length.

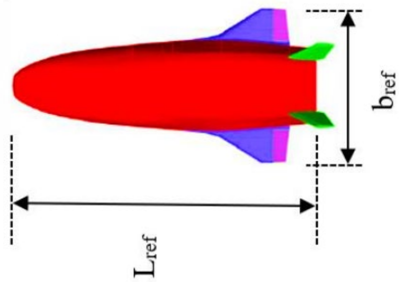


*Figure 2 – Elevons and ruddervators of the aeroshape [4],[5].*

The spatuled-body architecture allows to validate hypersonic aerothermodynamic design databases and passenger experiments, including thermal shield and hot structures, suitable for the successfully development of full-scale HSA [6],[7]. Within a typical mission scenario, in fact, HSA will encounter free-stream flows ranging from hypersonic to low subsonic speed.

The assessment of V-one longitudinal aerodynamics is undertaken with a Computational Fluid Dynamics (CFD) analysis with the goal to provide aerodynamic database (AEDB) to feed Flight Mechanics analyses. Both low speed and high-speed conditions were investigated at several angles of attack, $\alpha$. Indeed, CFD analyses, carried out with ANSYS FLUENT® tool, address the flowfield past the aircraft for $\alpha$ ranging from 0 to 15 deg, for Mach from 0.1 to 7 and for clean configuration (i.e., no aerodynamic surfaces deflected) only.

**Aerodynamic Flowfield Analysis**

Concept longitudinal aerodynamics is addressed in terms of force and moment coefficients, according to the ISO-1151 standard. Lift ($C_L$), drag ($C_D$), and pitching moment ($C_{Mx}$) coefficients are calculated according to the following equations.

$$\begin{cases} C_i = \frac{F_i}{q_\infty S_{ref}} & i = L, D \\ C_{M_x} = \frac{M_x}{q_\infty L_{ref} S_{ref}} \end{cases} \quad (1)$$

The moment coefficient refers to the aircraft moment reference centre (MRC), and the reference length, $L_{ref}$, coincides with the fuselage length, see Fig. 2. Then, the vehicle planform area is considered as reference surface, $S_{ref}$. Aerodynamic coefficients are obtained by means of steady state Reynolds Averaged Navier-Stokes (RANS) flowfield computations. The pressure-based coupled solver was used for all CFD analyses carried out at free-stream Mach number lower than $M_\infty$=0.3; for Mach higher than this threshold (i.e., $M_\infty$=0.3) the density-based solver was considered. In this case, the Flux Difference Splitting (FDS) second-order upwind scheme (least square cell based) has been used for the spatial reconstruction of convective terms, while for the diffusive fluxes a cell-centred scheme has been applied. An implicit scheme has been considered for time integration. For both uncompressible and compressible simulations, the k-$\omega$ SST turbulence model was used for Reynolds stress closure due to its ability to model separated flows and regions of flow circulation. Further, the ideal gas model was assumed for air. Recall that, even though CFD simulations have been carried out at hypersonic flow conditions (up to $M_\infty$=7), the ideal gas assumption was still valid. The reason is that the aeroshape features a very slender configuration and shall fly at rather low AoA (i.e., weak attached shock waves). A temperature-dependent formulation was considered for the specific heat at constant pressure, $c_p$, to accommodate the rather high flow energy at hypersonic speed [6]. Both unstructured and multi-block structured grids with an overall number of about 10M cells (half body) were considered for the flowfield computations. For each mesh, a body of influence surrounding the vehicle for grid refinement was considered, with the condition of $Y^{+}= O(1)$ at wall. Adiabatic wall is assumed at subsonic flow conditions, while the radiative cooled wall ($\varepsilon$=0.8) was assumed in the other cases. Sixty-four fully three-dimensional flowfield simulations were carried out and results, in terms of lift and drag coefficients, are summarized in Fig. 3.

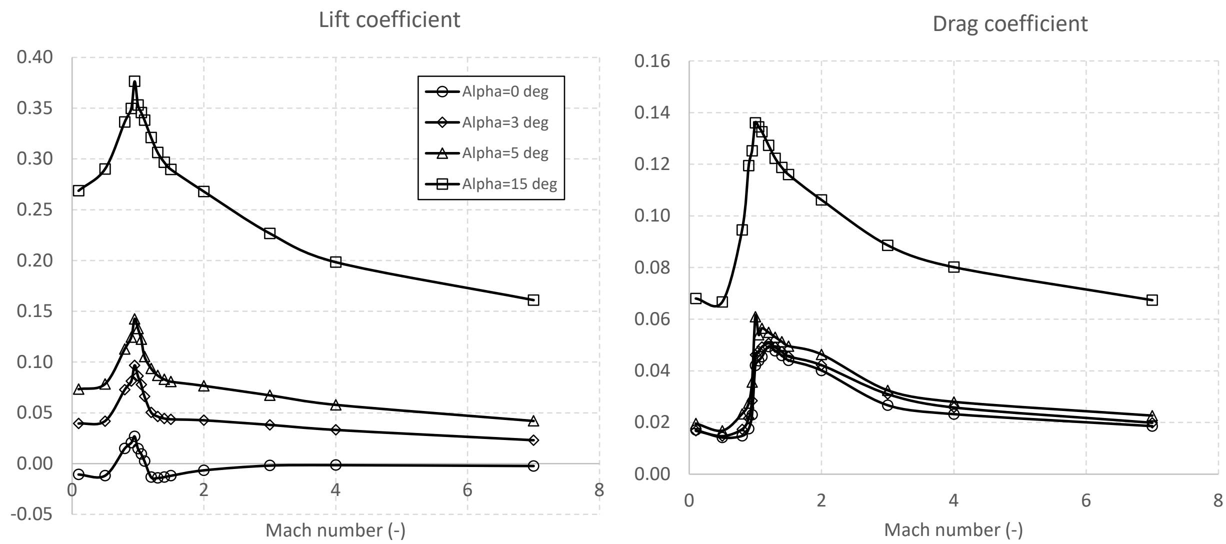


*Figure 3 – Lift and drag coefficients versus Mach at $\alpha$=0°, 3°, 5°, and 15°.*

Figure 3 provides aircraft $C_L$ and $C_D$ versus Mach at four angles of attack, namely $\alpha$=0°, 3°, 5°, and 15°. As shown, lift and drag coefficients rise in the transonic region and as expected increase as $\alpha$ increases. In particular, shock waves take place in the flowfield and determine a large increase of aerodynamic drag due to both wave drag and base drag which, in this speed regime, reach their maximum values. On the contrary, when Mach number further increases up to hypersonic flow conditions, aerodynamic coefficients decrease and reach a limit value, according to the Mach number independence principle.

## Summary

Flying test bed vehicles are an efficient way to experimentally validate next generation high-speed technologies. In this framework, the paper focused attention on the appraisal of the longitudinal aerodynamic performance of a streamlined flying test bed aircraft with a spatuled-forebody aeroshape. Several computational flowfield analyses are carried out at angles of attack ranging from 0 to 15 deg and for Mach numbers from 0.1 to 7.

Initial findings for the hypersonic speed range pointed out that the high streamlined sharp leading edges of the V-one aeroshape led to a rather low wave drag component. In fact, up to 5 deg angle of attack the drag coefficient is equal to about 0.02; while aerodynamic lift at this attitude is close to 0.05.

Low speed aerodynamic analyses show that the lift coefficient features a mostly linear lift curve slope as expected for this flow regime and wing profile. The rounded leading edges of the double-delta planform prevent the formation of strong vortices, which would otherwise result in sharp changes in lift curve slope at high AoA. Vortices were instead observed forming along the forebody of the aircraft, which would contribute to aerodynamic forces and stability. A comparison of a structured domain with an unstructured showed little difference in extracted coefficients.

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