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Aerodynamic and aerothermodynamic trade-off analysis of a small hypersonic flying test bed

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ABSTRACT

This paper deals with the aerodynamic and aerothermodynamic trade-off analysis aiming to design a small hypersonic flying test bed with a relatively simple vehicle architecture. Such vehicle will have to be launched with a sounding rocket and shall re-enter the Earth atmosphere allowing to perform several experiments on critical re-entry technologies such as boundary-layer transition and shock–shock interaction phenomena. The flight shall be conducted at hypersonic Mach number, in the range 6–8 at moderate angles of attack. In the paper some design analyses are shown as, for example, the longitudinal and lateral-directional stability analysis. A preliminary optimization of the configuration has been also done to improve the aerodynamic performance and stability of the vehicle. Several design results, based both on engineering approach and computational fluid dynamics, are reported and discussed in the paper. The aerodynamic model of vehicle is also provided.

1. Introduction

This paper deals with the aerodynamic and aerothermodynamic trade-off analysis of a re-entry flight demonstrator helpful to research activities for the design and development of a possible winged Reusable Launch Vehicle (RLV). Such experimental vehicles will have to be launched with a sounding rocket and shall re-enter the Earth atmosphere allowing to perform a number of experiments on critical re-entry technologies.

The flight shall be conducted at hypersonic Mach number, in the range 6–8 at moderate angles of attack (AoA). The flying test bed (FTB) configuration is designed to be allocated in the fairing of a small launcher and to withstand aerothermal loads of the re-entry flight. Therefore, a trade-off study involving several configurations have been taken into account and the preliminary aerodynamic and heating databases have been produced, as input for both the flight mechanics and thermo-mechanics design analysis. Such aerodynamic data have been used to generate a number of possible re-entry trajectories, able to fulfill program requirements.

For instance, the design and the development of next generation RLVs demands extensive numerical computations, in particular for the aerothermal environment the vehicle experiences, and large experimental test campaigns as well since considerable technological progress, validated by in flight operations, is mandatory. Up to now considerable progress has been achieved in hypersonics Computational Fluid Dynamics (CFD), and large wind tunnels exist (i.e., the CIRA Plasma Wind Tunnel “Scirocco”), but this is by far not sufficient for the design of an operational space vehicle. Therefore, it is advisable to gain first a practical RLV design knowledge by scaled low cost prototype vehicle flying partially similar RLV missions, to address practical experience on the key technologies within a realistic operational environment. In this framework the present paper reports on several analysis tools integrated in the conceptual design process of a small hypersonic FTB especially for what concerns the vehicle aerothermal design. Among others, we used computational analyses to simulate

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aerothermodynamic flowfield around the vehicle concept and surface heat flux distributions to design the vehicle Thermal Protection System (TPS). The vehicle detailed design, however, is beyond the scope of this work and the mission and system requirements will be defined only at the concept feasibility level.

The demonstrator under study is a re-entry space glider characterized by a relatively simple vehicle architecture able to validate hypersonic aerothermodynamic design database and passenger experiments, including thermal shield and hot structures, giving confidence that a full-scale development can successfully proceed.

A summary review of the aerodynamic characteristics of the FTB concepts, compliant with a phase-A design level, has been provided as well, according to the Space-Based design approach [1]. Accurate aerodynamic analyses, however, are very complex and time consuming, and are not compatible with a phase-A design study in which fast predicting methods are mandatory. Therefore, the evaluation of the vehicle AEDB was mainly performed by means of engineering tools, while a limited number of more reliable CFD computations was performed in order to verify the attained accuracy and to focus on some critical design aspects not predictable with simplified tools.

The engineering-based aerodynamic analysis was addressed using a 3D Supersonic–Hypersonic Panel Method code (S-HPM) that computes the aerodynamic characteristics, including control surface deflections and pitch dynamic derivatives, of complex arbitrary three-dimensional shapes using simplified engineering methods as Prandtl–Meyer expansion flow theory and tangent cone/wedge methods, together with the modified Newtonian one [2].

The code H3NS, developed at Aerospace Propulsion and Reacting Flows Unit of CIRA, was used to carry out the CFD analysis. It solves the thermal and chemical non-equilibrium governing equations in a density-based approach with an upwind Flux Difference Splitting (FSD) numerical scheme for the convective terms. H3NS solves the full Reynolds Averaged Navier–Stokes equations in a finite volume approach, with a cell centered formulation on a multi-zone block-structured grid [3].

For the numerical CFD simulations (continuum flow regime only) was chosen the non viscous Euler approximation which, even if it does not account for viscosity effects, is sufficient for the prediction of surface pressure distribution, position and intensity of shock–shock wave interactions. Viscous effects on vehicle aerodynamics have been assessed only at engineering level. Note that CFD (Euler or Navier–Stokes) analysis is nevertheless indispensable in preliminary design studies, keeping in mind the limited capability of engineering-based approach to model complex flow interaction phenomena and aerodynamic interferences. Moreover, CFD numerical computations allow to anchor the engineering analyses in order to verify the attained accuracy of these simplified analyses and to focus on some critical design aspects not predictable using engineering tools such as, for example, shock–shock interaction (SSI) phenomena on leading edges of both wing and tail, and real gas effects as well.

2. Flight scenario and vehicle description

The preliminary reference flight scenario foreseen for the vehicle is reported, together with the iso-Mach and iso-Reynolds curves, in the altitude–velocity space in Fig. 1.

The FTB concept is a wing–body configuration equipped with a delta wing and vertical tail embodying the critical technologies and the features of an operational system. The vehicle shall be characterized by a rather high aerodynamic efficiency, and therefore shall exhibit rather sharp nose and wing leading edges and shall fly at moderate AoA. It will provide aerodynamic and aerothermodynamic flight data

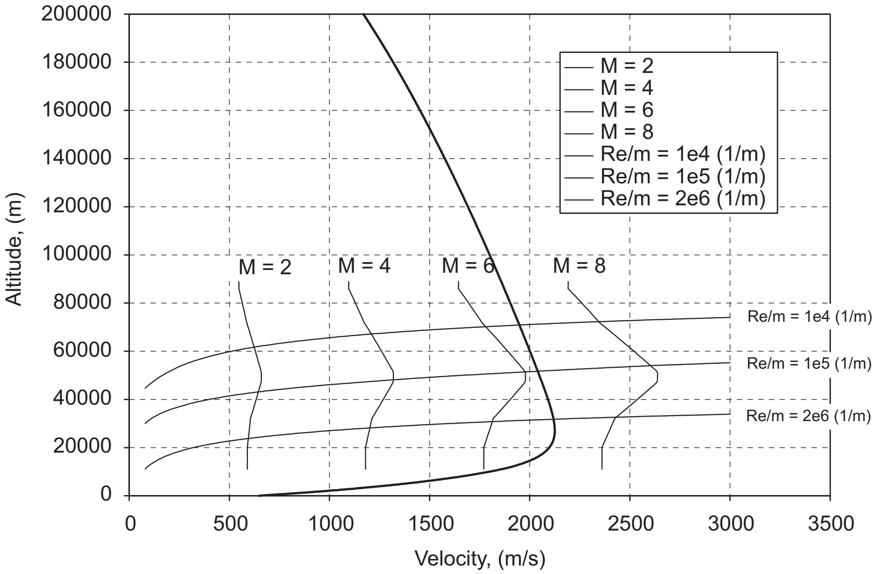

Fig. 1. FTB_4 preliminary design trajectory in the altitude-velocity map.