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Numerical investigations on the aerodynamics of SHEFEX-III launcher ☆

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ABSTRACT

The present work is a numerical study of the aerodynamic problems related to the hot stage separation of a multistage rocket. The adapter between the first and the second stage of the rocket uses a lattice structure to vent the plume from the 2nd-stage-motor during the staging. The lattice structure acts as an axisymmetric cavity on the rocket and can affect the flight performance. To quantify the effects, the DLR CFD code, TAU, is applied to study the aerodynamic characteristics of the rocket. The CFD code is also used to simulate the start-up transients of the 2nd-stage-motor. Different plume deflectors are also investigated with the CFD techniques. For the CFD computation in this work, a 2-species-calorically-perfect-gas-model without chemical reactions is selected for modeling the rocket plume, which is a compromise between the demands of accuracy and efficiency.

1. Introduction

SHEFEX (SHarp Edge Flight EXperiment) [1,2] is a hypersonic research project initiated by German Aerospace Center (DLR) in 2002. The objective of this project is to investigate the hypersonic flight techniques with a re-entry vehicle launched by a sounding rocket. The first two experiments (SHEFEX-I and SHEFEX-II) [3] were already conducted in 2005 and 2012, respectively. At present, DLR is working on the third experiment (SHEFEX-III). The selected launcher for SHEFEX-III is the Brazilian VLM-1 (Microsatellite Launch Vehicle-1) [4] which is being developed within a cooperation of DLR and Brazilian Institute of Aeronautics and Space (IAE). Here, it is planned to apply the hot separation technique, which is different from the first two SHEFEX flights that utilized the cold separation supported by a spring mechanism.

VLM-1 is designed as a three-stage-rocket without fins at the moment, which results in an aerodynamically unstable behavior. The S50 motor which is in development at IAE will be used for both the first and second stage of VLM-1. To steer the rocket and accommodate external disturbance, a movable nozzle is installed on the S50 motor. The movable nozzle is the unique control device on the rocket to restrict the pitch- and yaw-rate but leave the roll motion unrestricted. The 1st-stage will burn out and be dropped at the altitude of about 16 km, for which the aerodynamic effect is still pronounced. Therefore, the coast phase of the rocket should be as short as possible at staging. To meet this requirement, the application of the hot staging approach is necessary, which also has the advantage of lower cost.

The hot stage separation, which is also called fire-in-the-hole (FITH) in the literature [5–7], is to drop the burn out lowest stage directly by igniting the continuing-stage-motor. Usually, once the lowest stage is burning out, its thrust drops rapidly but can still support control forces.

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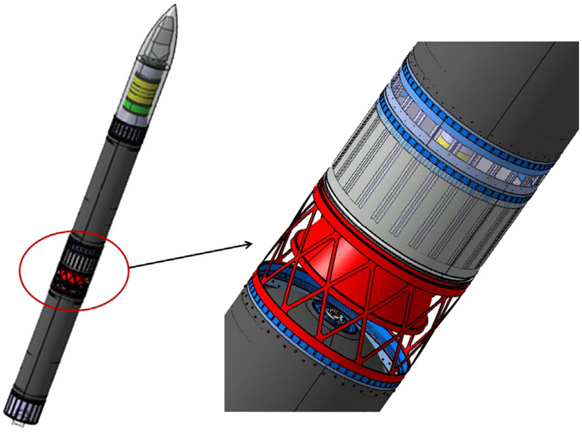

Fig. 1. VLM-1 and its inter-stage adapter.

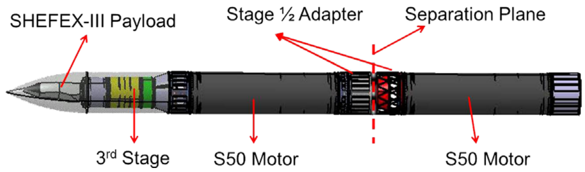

Fig. 2. VLM-1 with SHEFEX-III flight vehicle.

Then the continuing stage is ignited and the two stages disconnect almost immediately. Thereafter the staging is driven by the continuing-stage-motor: it exhausts gases into the inter-stage volume, which can form a high pressure region ahead the top of the first stage that pushes it away, and it also supplies thrust accelerating the continuing stage. To vent the exhaust gases from the continuing-stage-motor, it is planned to apply a kind of lattice inter-stage structure on VLM-1 (Fig. 1). The application of the open inter-stage adapter and the hot stage separation scheme induces serious aerodynamic problems.

In this work, the aerodynamic effects of the lattice inter-stage adapter of VLM-1 are investigated. The aerodynamic characterizations of the rocket with and without lattice inter-stage structure are compared and the flow topology in the inter-stage region is analyzed. Additionally the flow field of the rocket during the start-up transients of the 2nd-stage-motor is studied with time accurate Navier–Stokes computations. A 2-species-calorically-perfect-gas-model without chemical reactions is selected as an appropriate gas model to model the flow field with rocket plume, which is a compromise between the requirement of accuracy and efficiency in the computation. The selected gas model is also utilized to simulate the start-up transients of the 2nd-stage-motor and to investigate the different shapes of the plume deflector located on the top of the 1st-stage to guide the plume from the 2nd-stage-motor. All the efforts are to support the developing work of SHEFEX-III launcher, especially for the design of a reliable staging mechanism.

2. Aerodynamic characterization of the rocket

The DLR TAU-code has been used for the CFD computation in the present work. The TAU-code is a software system developed by the DLR Institute of Aerodynamics and Flow Technology for aerodynamic applications from low subsonic to hypersonic flow. The main module of TAU-code is a flow solver based on the finite volume method taking advantage of hybrid unstructured grids. The details of the TAU-code can be found in Ref. [8] and Ref. [9].

2.1. Computational geometry

Fig. 2 shows VLM-1 (configuration I). To increase the efficiency, the geometry of the rocket in the computations has been simplified (see in Fig. 3): the lattice inter-stage structure and the elements in the inter-stage cavity are removed from the computational geometry leaving only the nozzle and the aft skirt of the second stage; the aft skirt is represented by a thin panel ignoring the stringers; the 1st-stage is replaced by a simple cylinder without considering its nozzle and base cavity. As shown in Fig. 3, the nozzle of the 2nd-stage-motor is equipped with a closure, the flow in the nozzle is thus not considered before the ignition of the motor.

Moreover, the geometry of the rocket with closed inter-stage structure (Fig. 4, configuration-II) is introduced as a reference, which assists analyzing the aerodynamic effects of the open inter-stage structure.

2.2. Computational mesh

The computational mesh is generated by the commercial software CENTAUR [10] which supports a powerful hybrid mesh generator. The mesh of configuration-I (Fig. 5) is composed of a triangular surface mesh, a prismatic boundary layer mesh and a tetrahedral outer volume mesh (Fig. 6). The mesh resolution around the head and at the mouth of the inter-stage cavity has been strongly increased to capture the complex flow phenomena (see in Fig. 5). As it is not intended to resolve the recirculating flow in the cavity, the mesh in this region is set relatively coarse (Fig. 7) to improve the convergence of the steady-state computations.

For the simpler configuration-II, the computational mesh is composed of a quadrilateral surface mesh, a hexahedral boundary layer mesh and a prismatic outer mesh (see in Figs. 8 and 9), which is obtained through rotating a 2D axisymmetric mesh. All the meshes presented in this paper are the selected meshes after a grid convergence study [11].

2.3. Computation and analysis

The flow fields of the two configurations at different flight conditions are computed by the steady Reynolds-Averaged Navier–Stokes (RANS) solver of TAU-code along with Spalart–Allmaras one-equation turbulence model. The flight conditions of Mach 2.6 and Mach 1.5 at an altitude of 15.8 km are selected for the investigation. Mach 2.6 is the predicted condition for the separation of the 1st-stage. The computation of Mach 1.5 is for reference, which represents the low supersonic flight during the 1st-stage-boost. Figs. 10