High-fidelity simulation and low-order analysis for planetary descent investigation of capsule-parachute interaction

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Abstract. The project focuses on characterizing the unsteady dynamics of the parachute-capsule system during the descent phase of planetary entry in a supersonic flow regime. Currently, Large-Eddy Simulation, coupled with an Immersed-Boundary Method, is utilized to examine the time-evolving flow behavior of a rigid supersonic parachute trailing behind a reentry capsule as it descends through the Martian atmosphere. The flow is simulated at Ma=2 and Re=10^6. A massive GPU parallelization has been utilized to enable a high-fidelity resolution of the turbulent structures in the flow, essential for capturing its dynamic behavior. We demonstrate through low-order modeling of the unsteady turbulent wake of the capsule that low-frequency fluctuations within the wake are the primary trigger for flow instability in front of the canopy volume. Proper-Orthogonal Decomposition is utilized to investigate the system dynamics and analyze how various turbulence contributions influence the phenomenon.

Introduction

The failure of the ExoMars 2016 mission highlighted the persistent difficulties in forecasting and comprehending the dynamics of descent capsules affected by supersonic decelerators. Specifically, the unsuccessful landing of the Schiaparelli Entry, Descent, and Landing Module (EDM) was ultimately linked to an inadequate assessment of the interconnected oscillations between the descent module and the deployed parachute. Models and experimental assessments utilized to anticipate the capsule's response to the supersonic decelerator's impact were deemed inadequate, resulting in the mission's premature termination [1].

The inherent non-linearity of both fluid and solid behavior poses a significant challenge when studying unsteady compressible flows, particularly in the context of interactions between turbulent flows and solid structures [2,3]. This complexity is further compounded in scenarios involving unsteady compressible flows. Thus, the primary objective of this research is to develop effective approaches to investigate the interaction between compressible and turbulent flows, specifically focusing on the unsteady effects observed during flight [4]. The study relies on high-fidelity simulations of fluid dynamics, aiming to minimize the introduction of models and disturbances to provide the most accurate representation of flow dynamics under expected flight conditions. Currently, the analysis excludes the representation of flexible structures to concentrate solely on fluid-dependent effects and highlight the root causes of the observed phenomenon. Results from the baseline simulation are further analyzed to identify the primary trigger of the parachute bow shock instability, primarily attributed to low-frequency disturbances introduced by the wake of the descent module. This study builds upon previous analyses of descent module wake frequency conducted by the same authors [5]. Additionally, Proper-Orthogonal Decomposition is employed to gain deeper insights into turbulence dynamics, directly correlating frequency contents with oscillation patterns in the flow field that surrounds the canopy.

Computational setup and approach

Compressible Navier-Stokes equations are solved using the high-order finite difference solver STREAmS [6]. Turbulent structures are simulated through the implicit Large-Eddy Simulation (ILES) approach, eliminating conventional LES turbulence modeling. Instead, the numerical discretization provides artificial viscosity acting at small scales, effectively capturing turbulent behavior. Thus, the three-dimensional compressible Navier-Stokes equations solved are the following:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0,$$

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} + \frac{\partial p}{\partial x_i} - \frac{\partial}{\partial x_j}\Big(\mu\Big(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\Big)\Big) = 0,$$

$$\frac{\partial(\rho E)}{\partial t} + \frac{\partial(\rho E u_j + p u_j)}{\partial x_j} + \frac{\partial}{\partial x_j}\Big(\lambda\frac{\partial T}{\partial x_j}\Big) + \frac{\partial}{\partial x_j}\Big(\mu\Big(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\Big)u_i\Big) = 0,$$

where ρ is the density, u_i denotes the velocity component in the *i* Cartesian direction (*i =1,2,3*) and p is the thermodynamic pressure. With the intent of reproducing the effect of Mars' atmosphere, the fluid is considered as an ideal gas of CO_2; the ratio between the specific heat at constant pressure C_p and the specific heat at constant volume C_v is set to 1.3 while Prandtl number is 0.72. $E = C_v T + u_i^2/2$ represents the total energy per unit mass and the dynamic viscosity μ is assumed to follow the generalized fluid power-law. The thermal conductivity λ is related to μ via the Prandtl number with the following expression: $\lambda = C_p\mu/Pr$. The simulation is conducted at $Ma = 2$ and $Re = 10^6$ to replicate the conditions during parachute deployment. The reference fluid properties corresponding to the free-stream condition are obtained at an altitude of approximately 9 km from the planet's surface, simulated through an entry and descent trajectory in the Mars atmosphere of a generic reentry probe [7]. The flow domain selected to perform this first simulation has a size of $L_x = 20D,\ L_y = 5D,\ L_z = 5D$, where D is the maximum diameter of the descent module; parachute diameter is set to 2.57D. the mesh is a rectilinear structured grid that consists of $N_x \cdot N_y \cdot N_z = 2560 \cdot 840 \cdot 840$ nodes.

Computations have been carried out on CINECA Marconi100 cluster, computing on 64 GPUs.

Modal analysis and more specifically Proper-Orthogonal Decomposition (POD) has been applied to extract orthogonal basis which contribute to form a linear composition of the original flow field *q(x,y,z,t)* as follows [8]:

$$q(x, y, z, t) - \overline{q}(x, y, z) = \sum_j a_j(t)\phi_j(x, y, z)$$

where $\overline{q}$ represent the time-averaged flow obtained from q and φ_j and a_j are respectively the spatial mode and the temporal coefficients which drives them. Flow modes are sorted by their respective energy content: the first extracted are the most energetic and the last ones are the least energetic: further details can be found in [5].

Results and outcomes

In figure 1 we observe the three-dimensional representation of the flow around the descent module and its interaction with the parachute via the use of Q-Criterion method; capsule and parachute bow shock are visible. The Q-Criterion technique reveals turbulent structures in the wake of the

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module as they propagate downstream towards the decelerator. Near the position of the parachute bow shock, eddies originating from upstream experience a notable increase in size, forming larger vortices as they traverse the compression discontinuity. This transitional effect acts as the primary driver of the unsteady dynamics surrounding the decelerator in supersonic regimes. Turbulent fluctuations flowing downstream from the wake induce localized disturbances in the parachute shock speed, disrupting its equilibrium with the upstream flow and initiating continuous cyclic motion of the shock wave. This motion correlates with periodic variations in flow pressure within the canopy volume, ultimately influencing parachute performance. By employing low-order decomposition, we are able to further study the turbulence dynamics based on its energy contents and relative pattern of oscillations. In Figure 2, energy contours of selected flow modes in the region surrounding the capsule wake and the parachute are depicted. It is observed that the first modes, representing the most energetic fluctuations, correspond to the largest oscillation patterns and carry the lowest frequency content in the flow turbulence. Within these oscillation patterns, the canopy bow shock is distinctly visible at the first modes, exhibiting a disrupted shape due to the effect of unsteadiness. Notably, the canopy bow shock completely disappears at higher modes, indicating a direct relationship between shock motion and instability caused by the large fluctuations originating from the capsule wake. Specifically, the low-frequency, high-energy contents of the incoming turbulence contribute to the oscillations that propagate through the shock and toward the canopy. Based on these considerations, a zero-dimensional simplified model is built to describe the unsteady dynamics of shock motion and decelerator performance. Providing as an input only the lower frequency content of the wake dynamics, we observe comparable oscillations in both the canopy flow state and also the drag performance of the parachute.

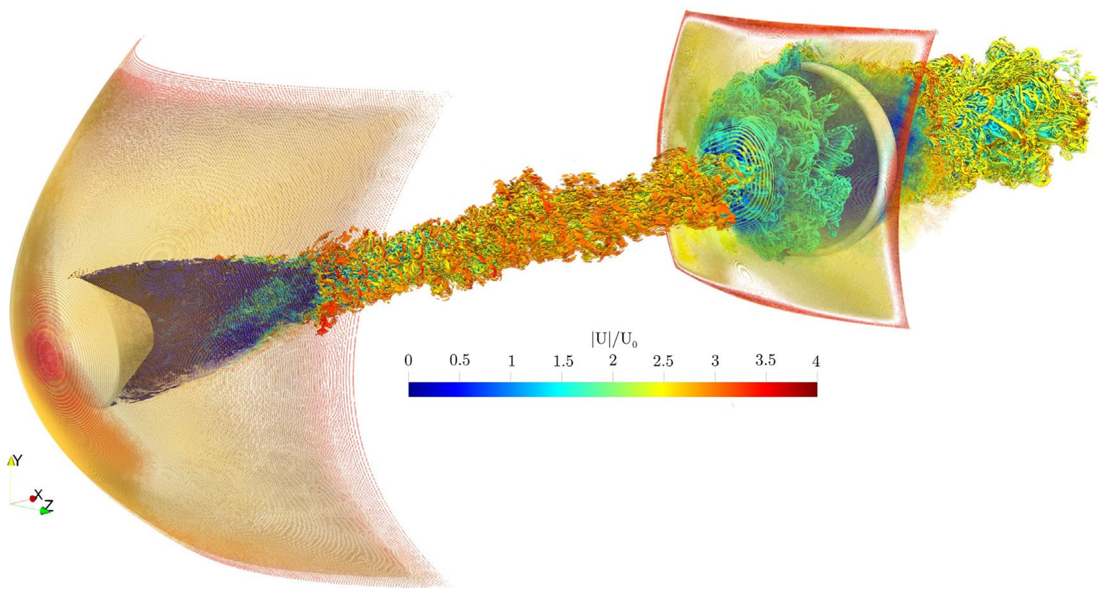

***Figure 1**: Q-criterion 3D representation of the flow around the descent module and parachute using non-dimensional velocity magnitude.*

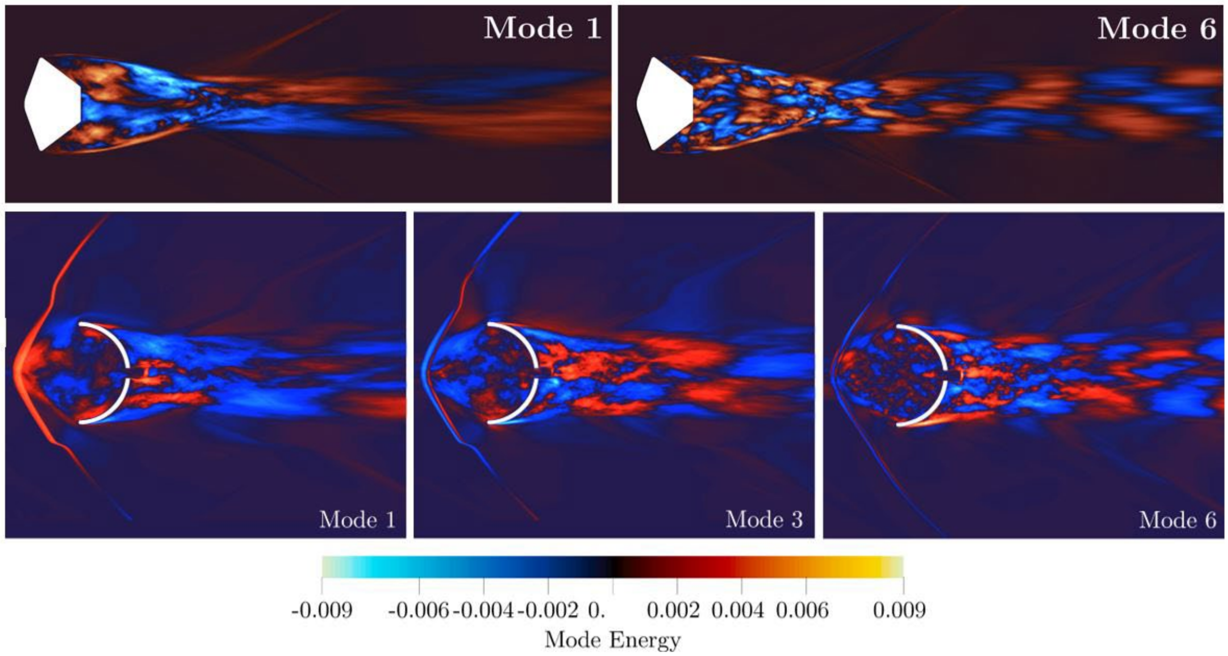

***Figure 2**: Energy contours for selected POD flow modes (y/D = 0 cross section, crop views). Descent capsule, top; parachute canopy, bottom.*

References

[1] T. Tolker-Nielsen. EXOMARS 2016 - Schiaparelli Anomaly Inquiry, 2017.

[2] X. Xue and Chih-Yung Wen. Review of unsteady aerodynamics of supersonic parachutes. Progress in Aerospace Sciences, 125:100728, 2021. ISSN 0376-0421. https://doi.org/10.1016/j.paerosci.2021.100728

[3] Nimesh, Dahal. Study of pressure oscillations in supersonic parachute. International Journal of Aeronautical Space Sciences, (19):24–31, 2018. https://doi.org/10.1007/s42405-018-0025-3

[4] B. S. Sonneveldt, I. G. Clark, and C. O'Farrell. Summary of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) Sounding Rocket Tests with a Disk-Gap-Band Parachute, AIAA 2019-3482. https://doi.org/10.2514/6.2019-3482

[5] L. Placco, M. Cogo, M. Bernardini, A. Aboudan, F. Ferri and F. Picano. Large-Eddy Simulation of the unsteady supersonic flow around a Mars entry capsule at different angles of attack. Aerospace Science and Technology, 143:108709, 2023. https://doi.org/10.1016/j.ast.2023.108709

[6] M. Bernardini, D. Modesti, F. Salvadore, and S. Pirozzoli. Streams: a high-fidelity accelerated solver for direct numerical simulation of compressible turbulent flows. Computer Physics Communications, 263:107906, 2021. https://doi.org/10.1016/j.cpc.2021.107906

[7] A. Aboudan, G. Colombatti, C. Bettanini, F. Ferri, S. Lewis, B. Van Hove, O. Karatekin, and Stefano Debei. Exomars 2016 schiaparelli module trajectory and atmospheric profiles reconstruction. Space Science Reviews, 214: 97, 08 2018. https://doi.org/10.1007/s11214-018-0532-3

[8] K. Taira, et al., Modal analysis of fluid flows: an overview, AIAA J. 55 (2017) 4013–4041. https://doi.org/10.2514/1.J056060