High-fidelity simulation of the interaction between the wake of a descent capsule and a supersonic parachute

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Abstract. The objective of the project is to analyze the unsteady dynamics of the parachute-capsule system in a supersonic airflow while descending during planetary entry. Currently, a combination of Large-Eddy Simulation and an Immersed-Boundary Method is being utilized to examine the evolving flow of a rigid supersonic parachute trailing behind a reentry capsule as it descends through the atmosphere of Mars. The flow is simulated at $Ma = 2$ and $Re = 10^6$. A massive GPU parallelization is employed to allow a very high fidelity solution of the multiscale turbulent structures present in the flow that characterize its dynamics. We show how strong unsteady dynamics are induced by the interaction of the wake turbulent structures and the bow shock which forms in front of the supersonic decelerator. This unsteady phenomenon called 'breathing instability' is strictly related to the ingestion of turbulence by the parachute's canopy and is responsible of drag variations and structure oscillations observed during previous missions and experimental campaigns. A tentative one-dimensional model of the flow time-evolving dynamics inside the canopy is proposed.

Introduction and case approach

The recent unsuccessful European missions (i.e. ExoMars 2016) proved how the prediction and the understanding of the dynamics of the descent capsule under the effect of a supersonic decelerator is still an open question in the active research scene that revolves around space exploration. The failure of Schiaparelli EDM landing indeed was ultimately caused by an improper evaluation of the coupled oscillatory motions existing between the descent module and the deployed parachute. The models and the experimental evaluations that were employed to predict the general behaviour of the capsule under the effect of a supersonic decelerator proved to be insufficient, triggering the premature end of the mission [1]. In this context, the main aim proposed by this research activity is to develop a novel technique to study effectively how compressible and turbulent flows interact with non-rigid structures, to properly evaluate and predict their non-steady behaviour. The description of this phenomenon is very elaborate, being affected by several uncertainties such as atmosphere fluctuations, unsteady flow dynamics and structure oscillations [2],[3]. The proposed approach involves Large-Eddy Simulations (LES) [4] for solving the multi-scale flow dynamics and Immersed Boundary Methods to deal effectively with moving solid boundaries [5]. A novel technique to deal with the fluid-structure interaction of compressible flows and thin membranes is in the process of development, starting from the existing IBM strategies. As a starting point for the implementation of the final configuration, a Large-Eddy simulation of

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a rigid mock-up parachute trailing behind a reentry capsule has been performed, showing both the potential of the LES approach and the primary dependence of the breathing phenomenon to the interaction of the turbulent wake of the module with the bow shock produced by the parachute.

Computational approach and simulation setup

Compressible Navier-Stokes equations are solved with the high-order finite difference solver STREAmS [4]. Turbulent structures are ultimately identified using the implicit large eddy simulation (ILES) approach; in this way, conventional LES turbulence modeling has been omitted, using instead the numerical dissipation given by the numerical discretization as artificial viscosity acting at small scales. Thus, the 3D Navier-Stokes equations solved are the following:

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

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_j u_i)}{\partial x_j}+\frac{\partial p}{\partial x_i}-\frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_i}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\delta_{ij}\right)\right)=0 \qquad (1)$$

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

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 Cp and the specific heat at constant volume Cv is set to 1.3 while Prandtl number is 0.72. $E = CvT + u_i^2/2$ 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: $\lambda = Cp\mu/Pr$. Convective and viscous terms are discretized using a sixth-order finite difference central scheme while flow discontinuities are accounted through a fifth-order WENO scheme. Time advancement of the ODE system is given by a third-order explicit Runge-Kutta/Wray algorithm. No-slip and no-penetration wall boundary conditions on the body are enforced through an Immersed-Boundary Method (IBM) algorithm.

The simulation was performed at $Ma = 2$ and $Re = 10^6$ to simulate the condition at which the parachute deploys. The reference fluid properties associated to the free-stream condition correspond to an altitude of about 9 km from the planet surface and have been obtained using a simulated entry and descent trajectory through the Mars atmosphere of a generic reentry probe [2].

The flow domain selected to perform this first simulation has a size of $Lx = 20D$, $Ly = 5D$, $Lz = 5D$, where D=3.8 m 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 $Nx \cdot Ny \cdot Nz = 2560 \cdot 840 \cdot 840$ nodes. The grid density changes in both axial and transverse directions, gaining resolution in the central portion of the domain; the position of the capsule nose is set at [1D, 0, 0] while the parachute center lies at [10D, 0, 0]. Computations have been carried out on CINECA Marconi100 cluster, allowing the domain parallel computing on a total of 64 GPUs.

Results

In figure 1 we observe the two-dimensional instantaneous flow field obtained by isolating the y=0 slice from the full 3D domain; Mach number contours are shown. Subsonic flow regions (in red), sonic regions (in white) and supersonic areas (in blue) can be identified. We observe the generation of two bow shocks ahead of the capsule and the canopy and the wake produced by the two bodies. The flow at the vent section is sonic. Pushed by the high pressure within the canopy and finding a larger passage section, it rapidly accelerates to the highest Mach number of the flow field. The breathing motion involves inhomogeneous fluctuations in pressure and density, resulting in substantial variations in drag, even though the canopy area remains constant. The primary cause of the breathing cycle appears to be the aerodynamic interaction between the wake of the capsule and the bow shock created by the parachute canopy.

Figure 2 shows density ratio contours in the area around the canopy. Different phases of the cycle that surrounds the periodic motion of the front bow shock along the flow direction: an increasing density inside the canopy pushes the shockwave away, allowing a larger flux to escape from the canopy (from [1] to [2]). Thus, this creates a decrease in the density that in turn draws back in the shockwave ([2] to [3]) and restarts the cycle ([3] to [4]). The

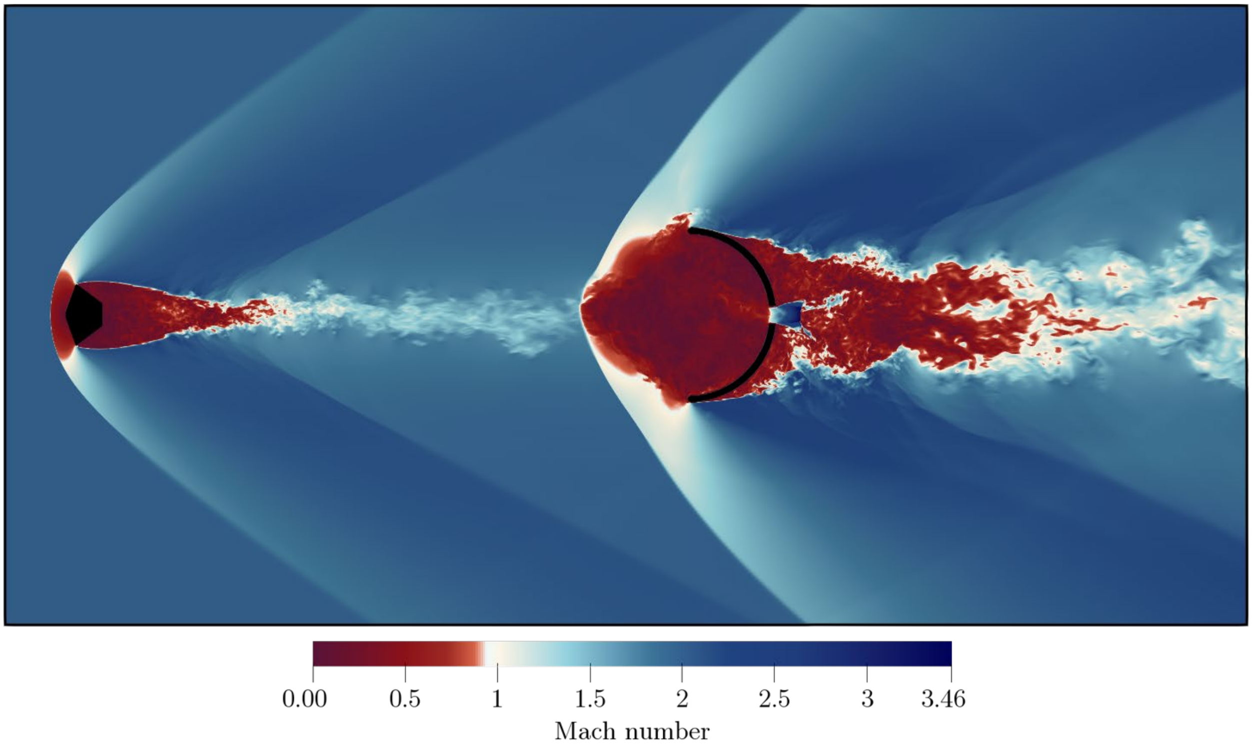

Figure 1: Instantaneous Mach contours (y = 0 cross section) of the simulated flow domain.

Conclusions

The present work proposes a high-fidelity time-evolving simulation of the interaction between the turbulent wake of a supersonic descent module and a generic rigid mock-up thick decelerator. We show how the critical ‘breathing’ instability associated to supersonic parachutes is intrinsically connected to the interaction of the turbulent wake flow of the descent module and the front bow shock produced by the decelerator. To overcome the limitation of the current setup and further extend the representation of its dynamics, the implementation of a novel immersed boundary method technique is in progress. This will require the solution of fluid-structure interaction of compressible supersonic flows and flexible thin membranes. The new framework will involve an extension of the current IBM module and a finite element method model to deal with flexible moving boundaries (zero-thickness), representing the very thin structure of the simulated decelerator. In this way, the approach in development will allow to represent properly both the entire deployment sequence and the system unsteadiness in all its components, thus providing the full representation of the ‘breathing’ phenomenon. The oscillation cycles align with the dynamics of the wake, as observed in previous experimental studies [3]. These cycles exhibit a frequency that is consistently around 0.16 in terms of the Strouhal number.

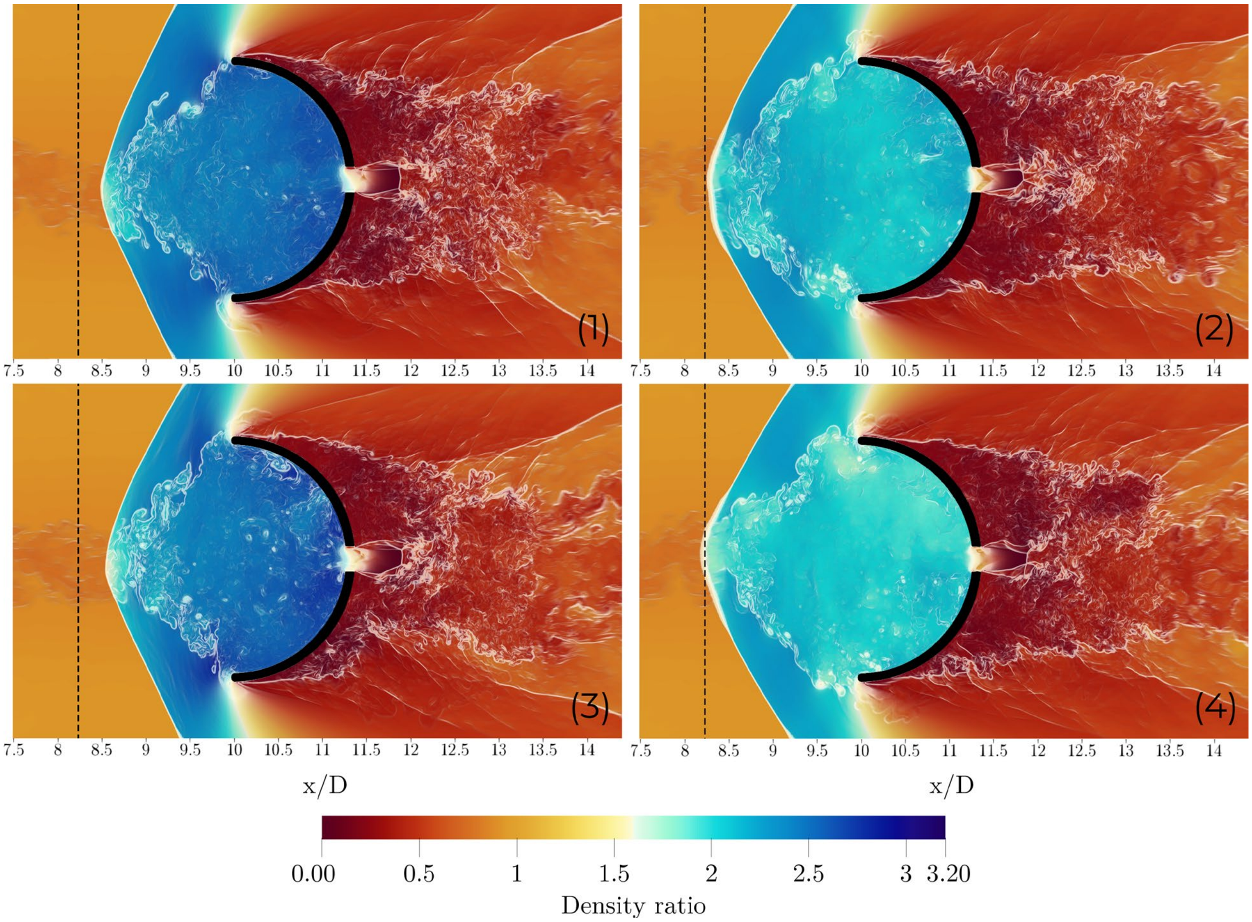

Figure 2: Instantaneous density ratio contours (y = 0 cross section) at different progressive timestep around the parachute canopy.

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