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Title of the thesis: *High-Fidelity Modelling of Supersonic Decelerators for Planetary Descent*

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Summary

Landing a spacecraft is among the most challenging phases of planetary exploration. After atmospheric entry, the descent module must decelerate from supersonic speed to a safe terminal velocity, relying on parachutes that operate in an atmosphere fundamentally unlike Earth’s in both composition and density. Despite decades of flight heritage, parachutes remain a critical vulnerability of the descent chain, with anomalies that have historically delayed missions on the ground and doomed them in flight. Among the open problems, poorly understood oscillations known as the “breathing” instability produce fluctuating drag and lateral loads that threaten the landing outcome: at full flight scale the canopy shock oscillates tens of times per second, cyclically loading and unloading a structure that must not fail. With upcoming programmes such as ExoMars “Rosalind Franklin” and Mars Sample Return depending on supersonic parachutes designed largely through empirical conservatism, understanding this phenomenon has become a priority.

This research tackles the problem through advanced computer simulations that resolve the turbulent flow around the spacecraft and its parachute in fine detail (Figure 1). Progressively building from the capsule wake to the full capsule–parachute system, across supersonic and subsonic regimes, the work identifies the physical mechanism of the “breathing” instability, demonstrates how the flight-proven disk-gap-band design suppresses it, and reveals how the canopy shape itself modulates the turbulent flow and the resulting pressure loads. A physics-based analytical model is also derived to predict the force oscillations at negligible computational cost, offering a practical tool for early-stage mission design.

Together, these results bridge the gap between empirical parachute design and the physics-based predictive capability required by future exploration missions, a step carried out in direct collaboration with the aerospace company responsible for ESA’s ExoMars parachute system and within a NASA-funded experimental effort.

Scientific summary of objectives, research methodology, main results, and achievements

Objectives. The primary objective of this work is to elucidate the physical mechanisms governing the aerodynamic instabilities of supersonic decelerators during planetary descent, with particular emphasis on the “breathing” instability. The research aims to: (i) characterise the turbulent wake environment into which the parachute is deployed; (ii) isolate and explain the fluid-dynamic origin of the “breathing” instability from first principles; (iii) assess how the disk-gap-band (DGB) parachute geometry mitigates these oscillations; and (iv) extend the investigation to the subsonic regime, linking canopy geometrical features to flow-driven pressure fluctuations. These studies constitute the most extensive application of Large-Eddy Simulation (LES) to unsteady turbulent flows around re-entry vehicles and parachutes for planetary exploration reported to date.

Research methodology. All numerical studies employ Large-Eddy Simulation of the compressible Navier–Stokes equations, implemented in the in-house solver STREAMS. Originally developed for canonical wall-bounded flows, STREAMS was extended during this research with an LES module incorporating the Wall-Adaptive Local-Eddy (WALE) viscosity model and Yoshizawa isotropic subgrid-scale closure. Complex geometries, the capsule and the parachute canopy, are handled via a Ghost-Point Forcing immersed boundary method. The solver employs sixth-order energy-preserving schemes hybridised with fifth-order WENO shock-capturing and third-order Runge–Kutta time integration, with CUDA acceleration enabling simulations on leadership-class EuroHPC supercomputers with domains exceeding 10^9 nodes. The supersonic cases reproduce Martian atmospheric conditions at Mach 2 in CO_2 ; the subsonic study is validated against a dedicated Particle Image Velocimetry (PIV) campaign performed at the University of Illinois at Urbana-Champaign within a

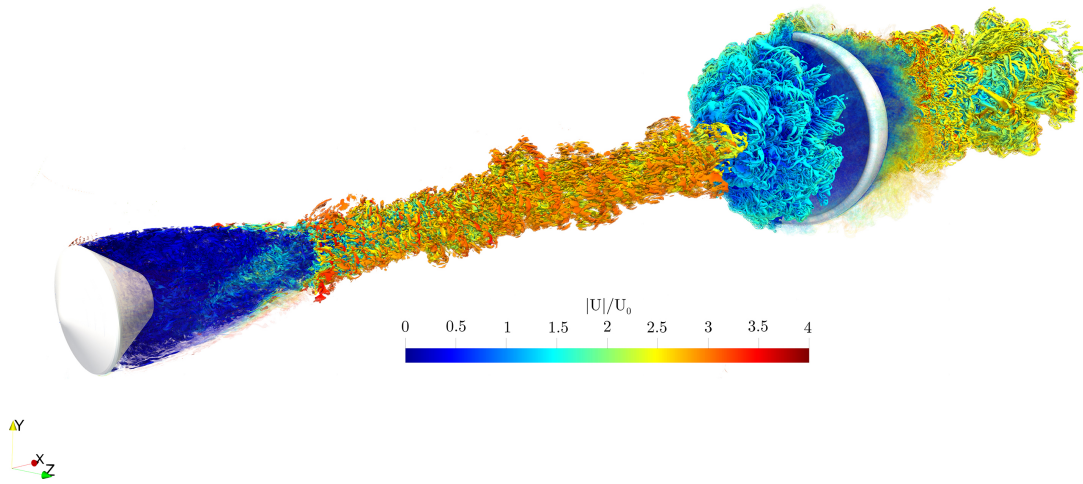


Figure 1: Snapshot of the simulated turbulent flow around the descent capsule and trailing parachute at supersonic speed. Three-dimensional flow visualisation reveals the complex flow dynamics surrounding the capsule and within the canopy.

NASA Early Stage Innovations project.

Main results. The turbulent wake generated by the descent capsule during supersonic flight sets the stage for all downstream instabilities. LES of the ExoMars capsule at Mach 2, across angles of attack from 0 to 15 degrees, reveals that flow separation generates an intense recirculation region whose size diminishes and turbulence intensity increases with attitude, a behaviour attributed to the stronger velocity gradients that enhance turbulence production [3]. Proper Orthogonal Decomposition confirms the dominance of large-scale structures: the ten most energetic modes recover the bulk of the unsteady wake behaviour, at Strouhal numbers $St \approx O(10^{-1})$. These structures constitute the upstream environment into which the parachute is deployed, providing the necessary input for the subsequent analyses.

Introducing a rigid hemispherical parachute into this wake, the “breathing” instability is isolated as a purely fluid-dynamic phenomenon [2]: the large upstream fluctuations destabilise the parachute bow shock, producing cyclic shock motion and corresponding drag-force oscillations, together with unbalanced lateral forces (Figure 2). The instability is therefore unavoidable, arising from the intrinsic imbalance between the incoming turbulent flow and the shock equilibrium. A zero-dimensional model based on mass and momentum balance across a control volume surrounding the canopy reproduces the LES drag signal at a fraction of the full simulation cost, offering a predictive tool for early-stage decelerator design [2].

Building on this understanding, the disk-gap-band geometry of the ExoMars “Rosalind Franklin” parachute is simulated under the same conditions, using the official canopy geometry envisioned to fly on the 2028 mission, in direct collaboration with Vorticity Ltd (UK), designers of the ExoMars parachute system [1]. Compared to the hemispherical canopy, the DGB reduces the RMS of the drag coefficient by a factor of 1.7 and transverse force fluctuations by a factor of 2.4. The gap outflow confines recirculation within the canopy cavity and pulls the bow shock closer to the disk, flattening it and suppressing the lateral oscillation modes responsible for the most energetic “breathing” contributions, with shock displacement reduced by up to a factor of 10. This provides the first flow-physics explanation of the stability of the flight-proven DGB design.

Finally, extending the analysis to the subsonic regime, the near-wake of a rigid inflated parachute with realistic creased geometry is resolved and validated against the dedicated PIV campaign at the University of Illinois at Urbana-Champaign [4]. Flow separation patterns differ markedly between “peaks” and “valleys” of the canopy creases, modulating the shear layer and triggering counter-rotating vortical structures that produce localised, self-sustained pressure fluctuations. These findings connect canopy manufacturing choices, such as the number of gores and suspension-line attachment, directly to their fluid-dynamic consequences.

Key achievements and impact. The contribution of this dissertation rests on three pillars. First, it establishes time-resolved, high-fidelity LES as an essential framework for planetary descent problems, in the most extensive application of the technique to decelerator aerodynamics reported to date. Second, it provides the first

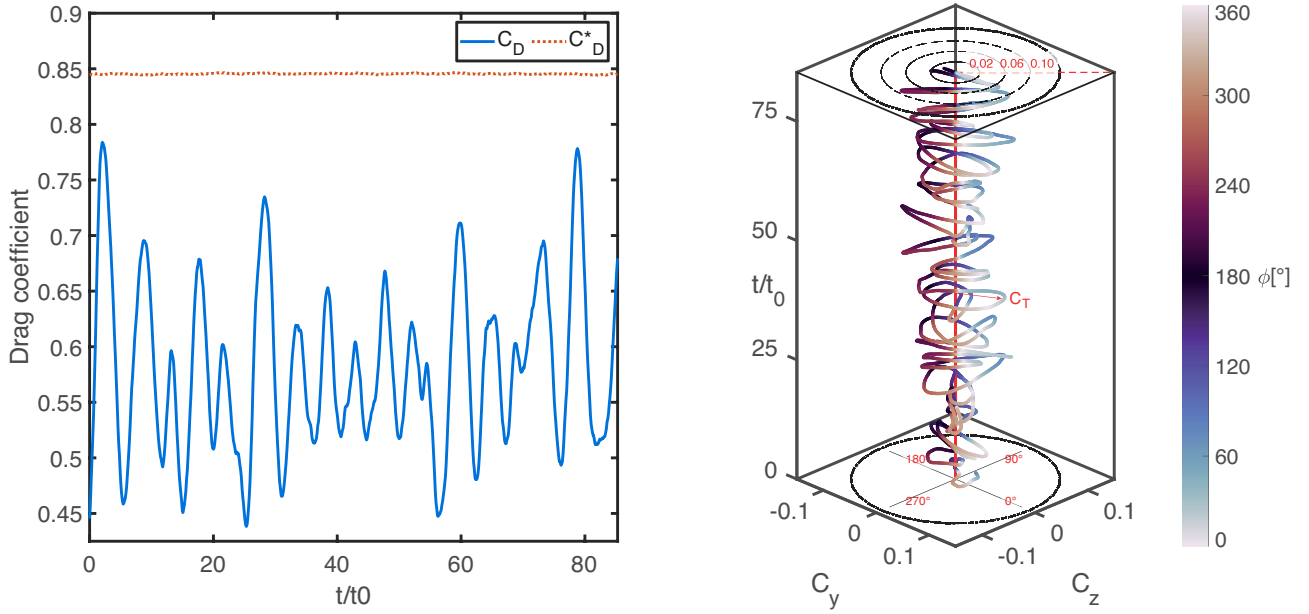


Figure 2: (Left) Time evolution of the parachute drag force with (C_D) and without the upstream capsule wake (C_D^*). (Right) Polar plot of the time-evolving lateral force C_T , showing the unsteady off-axis loading induced by the “breathing” instability.

explanation of the “breathing” instability from first principles, demonstrating that the phenomenon originates in the interaction between the turbulent wake of the descent module and the bow shock of the trailing canopy, and it delivers a physics-based zero-dimensional model that reproduces the resulting drag oscillations at negligible computational cost [2]. Third, it gives the first flow-physics rationale for the stabilising effect of the DGB configuration, obtained on the official ExoMars 2028 geometry with Vorticity Ltd [1], and extends the interpretation to the subsonic regime, where the link between canopy geometry and the turbulent near-wake is established and experimentally validated within a NASA ESI project with the University of Illinois at Urbana-Champaign [4]. The direct engagement of ESA mission parachute designers and of NASA-funded experimental partners underscores the transfer of these insights into engineering practice, bridging empirical conservatism and the physics-based predictive capability indispensable for future exploration missions.

Output and selected publications

This research was recognised with the ERCOFTAC Milton Van Dyke Award. It has resulted in publications in Q1 journals, and has been presented at eleven international conferences, including APS-DFD, DLES, ETMM and the International Planetary Probe Workshop. The simulations were enabled by EuroHPC Regular Access and CINECA ISCRA-B/C allocations totalling more than 400,000 GPU-hours on pre-exascale machines, awarded to the author as Principal Investigator. The experimental component was carried out as a visiting researcher at the University of Illinois at Urbana-Champaign within a NASA Early Stage Innovations project, alongside the industrial collaboration with Vorticity Ltd, designers of the ESA ExoMars parachute.

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