High-Fidelity Modeling of Supersonic Decelerators for Planetary Descent

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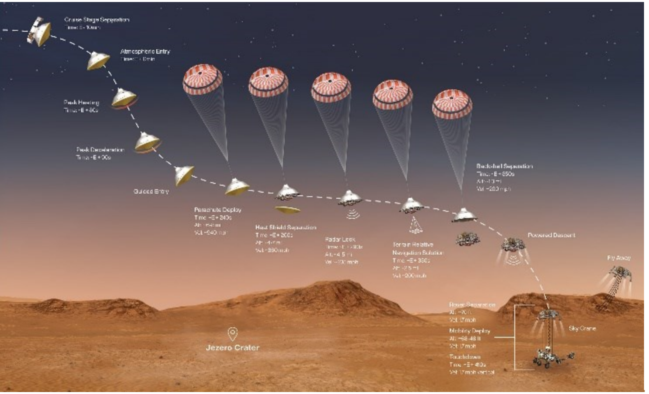
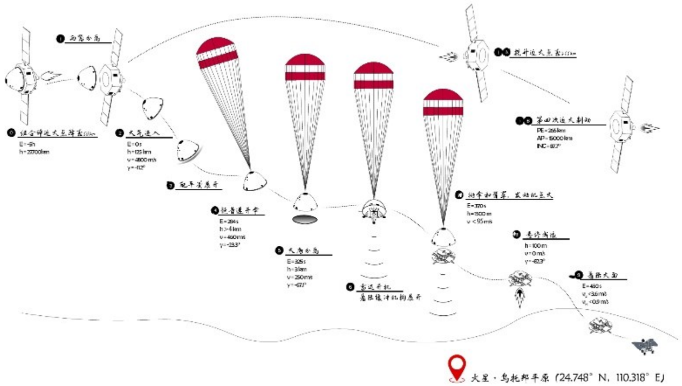
Admission to the first year – 09/11/2022

The context

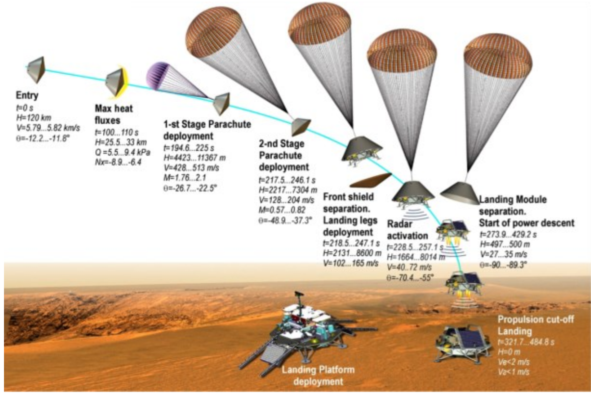
Recent space exploration mission – Mars



Perseverance – Feb. 2021
(*NASA/JPL-Caltech*)



Tienwen-1 – May 2021
(*Info Shymkent*)



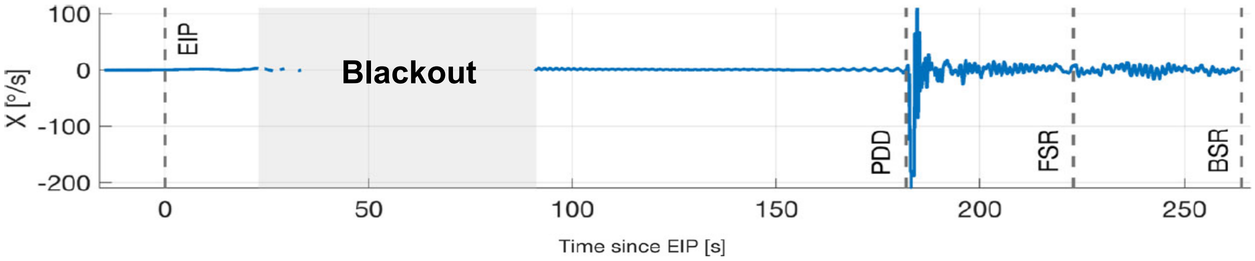
Rosalind Franklin – TBD
(*ESA/AOES Medialab*)

- Entry, descent and landing are considered the most critical phases for space exploration missions.

Motivation

➢The behaviour of the descent capsule under the effect of a supersonic decelerator is still an open question – unsteady turbulent supersonic flow couples with shock effects.

- "Schiaparelli's trajectory and systems status were nominal up to the moment of parachute deployment" from *Schiaparelli Anomaly Inquiry Report, 2016*

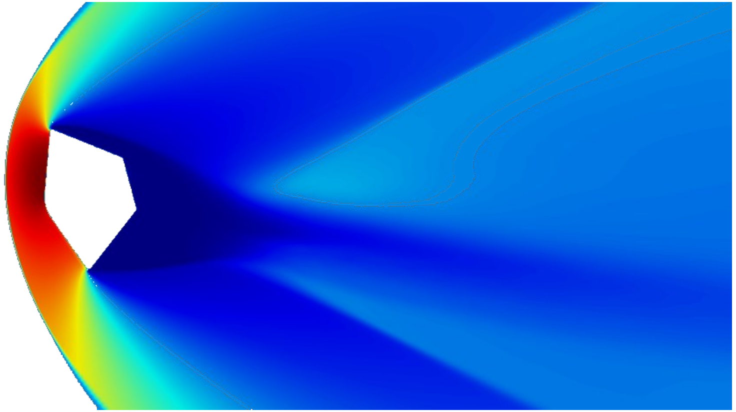


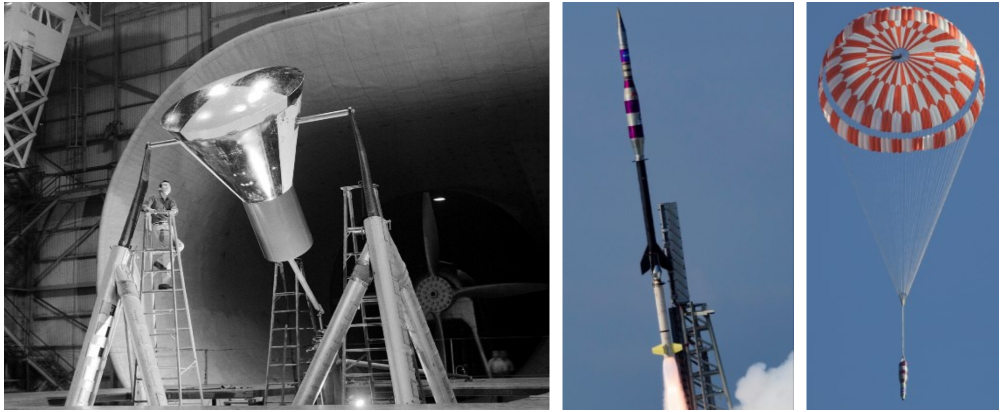
A. Aboudan et al. - 2018

- At the first oscillation after PDD, the IMU saturated, measuring a pitch angular rate larger than 187.5 deg/s compared to the maximum estimated value of 30 deg/s. The reason being "**an insufficient fidelity of the modelling of the complex dynamics during inflation, or by an inaccurate reconstruction of the dynamic conditions at the moment of parachute deployment**"

Possible methodologies

➢ **The crucial aspect is the unsteadiness of the flow generated by the interaction of the forebody's wake with the deployed parachute.**





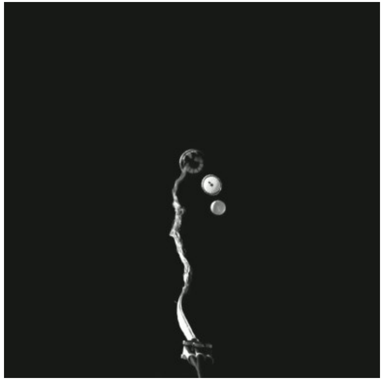
(NASA, Mercury Project and ASPIRE Project)

- Standard (RANS) analysis are not able to reproduce the non-stationary nature of the flow.
- Experimental campaigns are difficult to execute; they do not perfectly replicate operative conditions and costs are prohibitive.

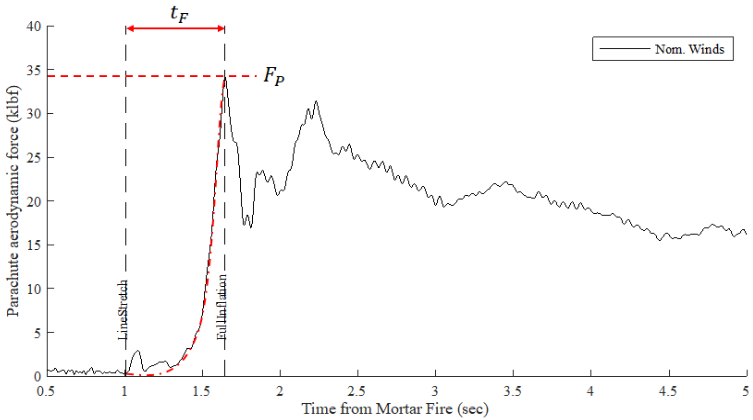
Main aim

- **Development of a fluid-structure interaction framework to investigate aerodynamic phenomena concerning the descent phase of a capsule:**
  - Analysis of the interaction of the wake produced by the capsule and the inflated decelerator shape.

(NASA, Mars 2020 Deployment)



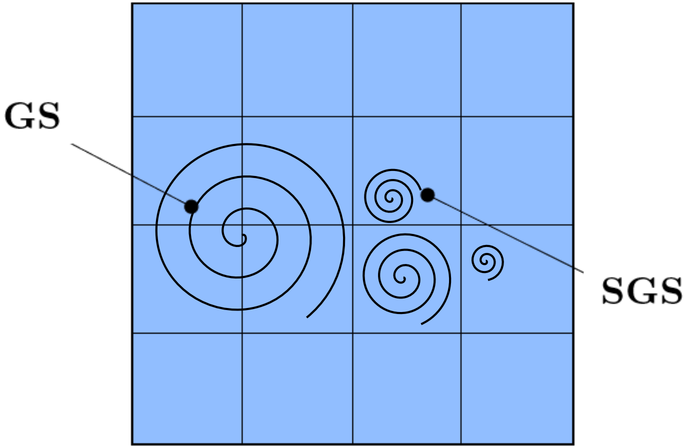
Inflation sequence and time

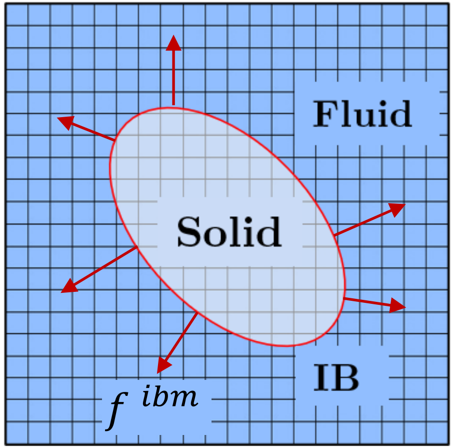


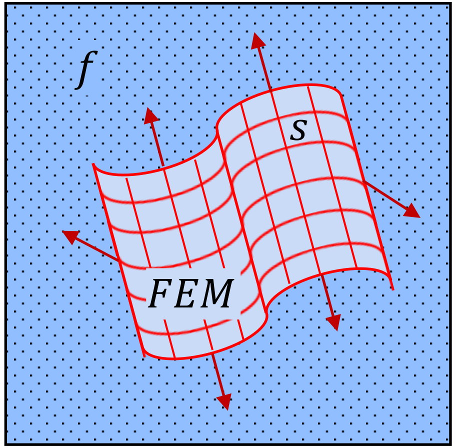
Peak loadings

'Breathing' instabilities

Proposed computational framework







- Large-Eddy Simulations (**LES**) to obtain a precise time-evolving development of the wake flow behind the capsule. **GPU parallel computing** enables its use.
- Immersed-Boundary Method (**IBM**) to represent a infinitesimal thickness interface in the flow field and evaluate the fluid-structure force exchange.
- Finite-Element Method (**FEM**) to deal with structure deformations – thin shells elements to model surface wrinkling and displacements.

Tasks approach and progression

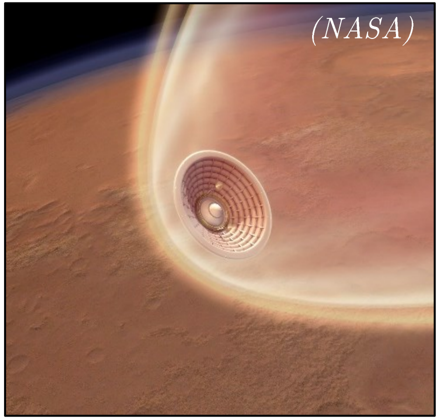
- **TASK #1**

Immersed-Boundary method; modify the existing approach and apply novel techniques to deal with **thin interfaces** moving in a compressible flow.

- **TASK #2**

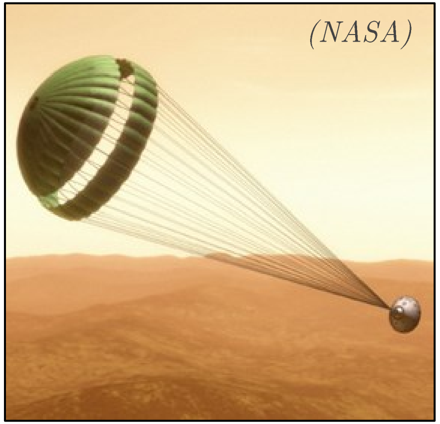
Develop a **solid solver** based on thin-shell elements to evaluate **stress-strain** on the immersed body – wrinkling, flapping, solid contact, etc.

Coupled Framework



- **TASK #3**

Test case simulation of the full deployment sequence of a flexible decelerator (Disk-Gap Band or HIADs) to evaluate **dynamics** and **performance**.



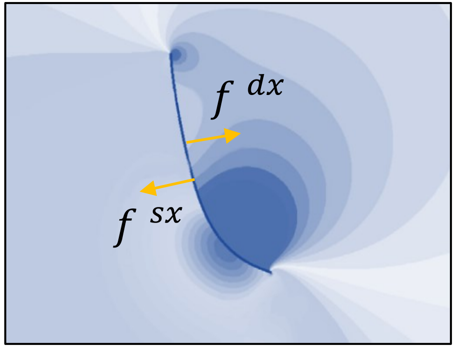
Task #1 – The flow solver

- **Couple the compressible flow opensource solver (*STREAmS*) with an innovative Immersed-Boundary Method module for thin interfaces:**
  - *STREAmS* employs Large-Eddy Simulation (**LES**) to solve the turbulent supersonic flow that surrounds the descent system – Massive **GPU parallelization** allows the computation.

Current state-of-the-art for flow solving.

  - Immersed Boundary Method module (**IBM**) to deal with the force exchange between the fluid and the infinitesimal-thickness structure representing the decelerator.

$$\frac{\partial W}{\partial t} = -\frac{\partial F_j(W)}{\partial x_j} - \frac{\partial F_{vj}(W)}{\partial x_j} + f_{IBM}$$



First test-case: thin interface moving in a supersonic flow – testing and validation.

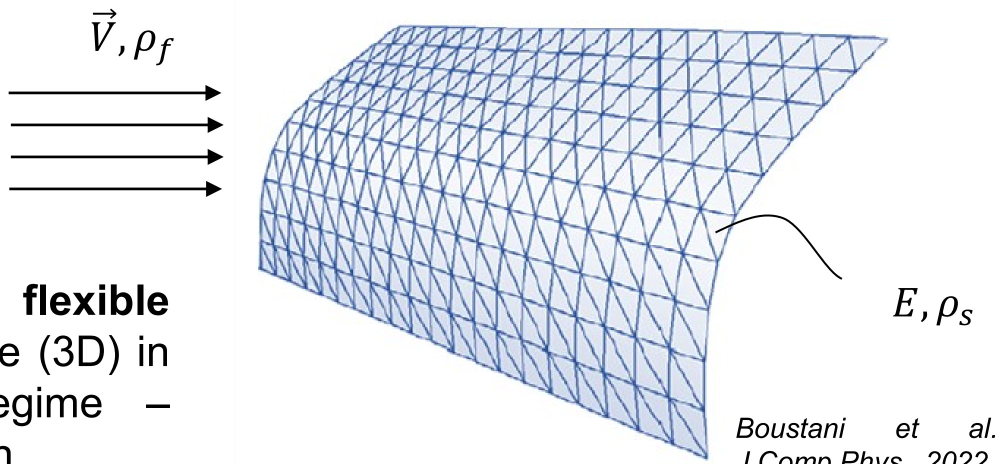
Task #2 – The solid solver

➢ Integrate a solid solver that deals with structure deformation/displacement:

- A Finite-Element Method (**FEM**) module for thin shell structure dynamics will be developed – (e.g. Kirchhoff & Love).

- Perform Fluid-Structure Interaction problems in *STREAmS*.

Second test-case: **flexible** line (2D) and surface (3D) in a compressible regime – testing and validation.

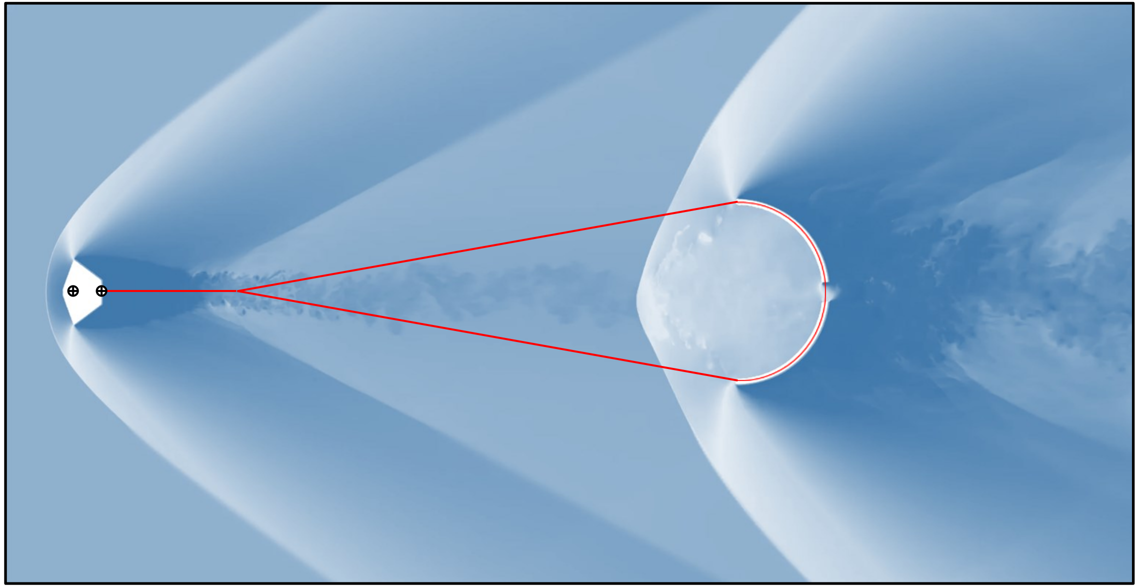


Boustani et al. J.Comp.Phys., 2022

Task #3 – Case study

- **FSI supersonic decelerator simulation – full deployment and dynamics evaluation.**

  - Investigate the unsteady aerodynamic phenomena pertaining the fluid-structure interaction scenario of a flexible and thin decelerator moving and deforming a supersonic, turbulent flow (e.g. Parachute deployment in the Mars atmosphere).



GANTT Chart

Level	Activity description	Year 1				Year 2				Year 3			
Event	Research proposal presentation	▽											
1	Bibliographical research and framework setup	■	■	■									
2	Development of the thin-shell IBM module and 2 DOF rigid decelerator simulation test case			■	■	■	■						
Event	Admission to 2nd year					▽							
3	Development of the FEM model for flexible structures - software implementation					■	■	■					
4	2D Simulation of flexible decelerator with descent module at supersonic condition (line)							■	■	■			
Event	Admission to 3rd year									▽			
5	3D Simulation of the deployment of a flexible decelerator with descent module at Mach 2									■	■	■	■
6	Writing thesis and research report				■				■	■	■	■	■
Event	Admission to final exam												▽

Final remarks

➢ Summary of the proposed activity

- Development of a fluid-structure interaction framework to investigate aerodynamic phenomena concerning the descent phase of a capsule - analysis of the interaction of the wake produced by the capsule and the inflated decelerator shape.

  - Implementations on the in-house software flow solver STREAmS – high fidelity fluid simulations coupled with a thin-interface solid solver – parallelized on GPU.

  - Propose a feasible alternative to experimental campaigns in order to provide accurate and employable results for the design of future missions.

Thank you for the attention

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