Numerical Aero-Thermal Investigation for a Science Payload in a Dust Devil Boundary-Layer on Mars

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Active Space Technologies GmbH

- European based company positioning its services in the global markets of aerospace, defense, automotive, nuclear fusion, and scientific sectors
- Technology cooperation partner of DLR
- Well founded experience with NASA, ESA, EU projects
Active Space Technologies GmbH

Main areas of expertise:

- Thermal Engineering
- Mechanical Engineering
- Support System design and manufacturing
- Project Management, System Engineering and PA/QA
- Design of instruments for space exploration
Main projects

| MASCOT – Mobile Asteroid Surface Scout, DLR Project |
Main projects

| PEASSS – Piezoelectric Assisted Smart Satellite Structure, FP7, EU Project

Introducing PEASSS
Piezoelectric Assisted Smart Satellite Structure

Development and demonstration of piezo actuated “smart structure” for pointing of optical instruments/sensors and power harvesting, fiber bragg gratings for strain measurement, and next generation of small satellite electronics.

The objective of the PEASSS project is to develop, manufacture, test and qualify “smart structures” which combine composite panels, piezoelectric materials, and next generation sensors, for improved pointing accuracy and power generation in space.
Main projects

InSight – NASA Project
Contents

| Introduction to the Martian Mission |
| Geophysical Science Payload |
| Dust Devils overview |
| Numerical Aero-thermal Investigation |
  > Problem statement and physical assumptions |
  > Pre-processing |
  > Physics models and Boundary Conditions |
  > Results |
| Stability Analysis |
| Conclusions |
InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) is a NASA Discovery Program mission - planned for a March 2016 launch - that will place a single geophysical lander in the southern Elysium region of Mars to study its deep interior.
InSight: Science Objectives

- Uncover how a rocky body forms and evolves to become a planet by studying the size, thickness, density and overall structure of the Red Planet's core, mantle and crust, as well as the rate at which heat escapes from the planet's interiors.
InSight Science Payload

- The **Seismic Experiment for Interior Structure (SEIS)** - provided by the French Space Agency (CNES) - which will take precise measurements of quakes and other internal activity on Mars to better understand the planet's history and structure.

- The **Heat Flow and Physical Properties Package (HP³)** instrument - provided by the German Space Agency (DLR) - which determines the geothermal heat flux by penetrating down into the surface of Mars to at least 3 meters.
Geophysical Science Payload: HP³
Dust Devil Winds

Dust devils are small whirlwinds which form when surface insolation leads to a superadiabatic lapse rate, causing an unstably stratified atmosphere and strong convection. They are common atmospheric phenomena on both Earth and Mars.

Arizona desert, USA, 08/06/2005
Dust Devil Winds formation

Dust devils are upward moving, spiraling flows made visible by entrained dust and sand. The term “dust devil” is used to refer to sustained, particle-loaded convective vortices to distinguish them from vortices that form in the same way but are too weak to pick up materials and become visible.

Generalization of wind speeds within a dust devil

R is the radius of the dust column, U, V and W are the radial, tangential and vertical wind speeds, respectively. Maximum speeds are given as ~10 m/s, typical of many dust devils, but can be up to 25 m/s.

Dust Devils on Earth and Mars, M. Balme - R. Greeley, 2006
Martian Dust Devils

- Comparison between Martian and Terrestrial Atmospheres

<table>
<thead>
<tr>
<th>Atmosphere (composition)</th>
<th>Mars</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (95.32%)</td>
<td></td>
<td>Nitrogen (77%)</td>
</tr>
<tr>
<td>Nitrogen (2.7%)</td>
<td></td>
<td>Oxygen (21%)</td>
</tr>
<tr>
<td>Argon (1.6%)</td>
<td></td>
<td>Argon (1%)</td>
</tr>
<tr>
<td>Oxygen (0.13%)</td>
<td></td>
<td>Carbon dioxide (0.038%)</td>
</tr>
<tr>
<td>Water vapor (0.03%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitric oxide (0.01%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The effect of the atmospheric heat flux is reduced due to the low air density and the nearly complete absence of water vapour. This leads the diabatic heat flux to higher values than on Earth.

- Martian dust devils can be considerably larger than their terrestrial analogues.

- The variety in sizes, the numerous occurrences and the effective dust-lifting ability suggest that dust devils play an important role in the thermal structure of the atmospheric convective boundary layer of Mars.

The maximum spin velocity of dust devils on Earth is about 50 mph (80.5 kph), while dust devils on Mars may spin up to 200 mph (322 kph) because of the thin atmosphere.
Velocity Profile in a Dust Devil BL

4-Region Model for Determining the Velocity in a Dust Devil BL on Mars

- $V_p = 75 \text{ m/s}$
- $z_0 = 0.01 \text{ m}$
- $v = 8.15 \times 10^{-4} \text{ m}^2/\text{s}$
- $y_{log-max} = 2787$
- $u^*/u'' = 0.51$
- $k = 0.4$

- $Z_{log-max}$
- $Z_0$
- $Z_{\infty}$

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- Stability Analysis
- Conclusions
Numerical Aero-thermal Investigation

The CFD investigation aims to predict the aerodynamic loads and the heat transfer coefficient on the surface of the HP³ Support Structure during and after exposure to momentary dust devil winds up to 75 m/s.

**Physical Assumptions**

> Subsonic flow (M≈0.3) with the 4-region logarithmic law for the velocity in a dust devil BL on Mars
> Aerodynamic loads estimation based on the daytime ambient density, which ranges 0.015-0.023 kg/m³
> Worst thermal case scenario referred to Min Early Large Dust Storm conditions in Survival Mode
> Uniform Wall Temperature on the instrument (maximum and minimum survival HP³ temperatures)
> Martian Atmosphere modeled as Carbon Dioxide (CO₂)
## Martian Air Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity on Mars surface</td>
<td>$g = 3.711 , \text{m/s}^2$</td>
</tr>
<tr>
<td><strong>Maximum Air Temperature</strong></td>
<td>$T = 238.4 , \text{K}$</td>
</tr>
<tr>
<td>Air density</td>
<td>$\rho = 0.02377 , \text{kg/m}^3$</td>
</tr>
<tr>
<td><strong>Air dynamic viscosity</strong></td>
<td>$\mu = 1.19 \times 10^{-5} , \text{kg/m} \cdot \text{s}$</td>
</tr>
<tr>
<td>Air kinematic viscosity</td>
<td>$\nu = 5.02 \times 10^{-4} , \text{Pa/s}$</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>$P_{\text{atm}} = 1066 , \text{Pa}$</td>
</tr>
<tr>
<td>Mass of the HP$^3$ (after mole deployment)</td>
<td>$m = 1.377 , \text{kg}$</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>$k = 0.01207 , \text{W/m-K}$</td>
</tr>
</tbody>
</table>
Original Design and Simplified Model
Computational Domain

Test section for the Wind Tunnel

2 H \times 4 W \times 6.8 L

Tether region

Grapple

Mole

Top wall

Struts

Inlet

Outlet

Side walls

Floor

Contents

Introduction to the Martian mission

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Stability Analysis

Conclusions
Volume Mesh

Tetrahedral volume mesh, 3,761,401 cells
Setting up the Physics Models

- Steady
- Gravity
- User defined CO₂ Gas
  → Incompressible
- Segregated Flow
  → Segregated Fluid Temperature
- Turbulent
  → Realizable K-epsilon model
  → High y+ Wall Treatment
- RANS – Reynolds Average Navier Stokes
Boundary Conditions

- **Inlet** of the wind tunnel
  - Velocity Inlet
  - User defined Field Function for the velocity profile
  - Flow direction normal to the tether compartment of the instrument

- **Outlet** of the wind tunnel
  - Pressure Outlet

- **Top and Side Walls** of the wind tunnel
  - Adiabatic Slip walls

- **Floor** of the wind tunnel
  - Adiabatic No-Slip wall

- **HP³ Support Structure** (Tether, Mole, Grapple, Struts Regions)
  - No-Slip wall, constant temperature
Velocity Contour and Vectors
Pressure Contours
Heat Transfer Coefficient – Hot Wall

→ $T_{\text{wall}} = 328$ K, maximum HP$^3$ survival temperature
→ $T_{\text{ref}} = 238.4$ K, maximum thermal case temperature
Heat Transfer Coefficient – Cold Wall

→ $T_{\text{wall}} = 148 \text{ K}$, minimum HP$^3$ survival temperature
→ $T_{\text{ref}} = 197.62 \text{ K}$, minimum thermal case temperature

<table>
<thead>
<tr>
<th>Region</th>
<th>$h_{\text{ave}} \text{ [W/m}^2\text{K]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grapple</td>
<td>20.2</td>
</tr>
<tr>
<td>Mole</td>
<td>12.76</td>
</tr>
<tr>
<td>Struts</td>
<td>10.5</td>
</tr>
<tr>
<td>Tether</td>
<td>9.48</td>
</tr>
</tbody>
</table>
There is the foreseen possibility of deploying the HP³ in an area with a ground slope.

- Maximum slope of 15°

- Comparison between the tipping moment due to the wind Drag force and the stabilizing moment resultant from the body’s weight.

- The instrument is said to be stable only if the Drag moment does not exceed the Weight restoring moment

- Safety margins over 50 %
HP³ Configuration at 0° and 15° slope
## Stability Margins after Mole Deployment

<table>
<thead>
<tr>
<th>Properties After Mole Deployment</th>
<th>0° Slope</th>
<th>15° Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>M [Mass of the instrument, kg]</td>
<td>1.377</td>
<td>1.377</td>
</tr>
<tr>
<td>W [Weight, N]</td>
<td>5.11</td>
<td>5.11</td>
</tr>
<tr>
<td>Weight moment arm [m]</td>
<td>0.165</td>
<td>0.124</td>
</tr>
<tr>
<td>Mw [Weight Moment, N·m]</td>
<td>0.843</td>
<td>0.637</td>
</tr>
<tr>
<td>A [Frontal Area, m^2]</td>
<td>0.0827146</td>
<td>0.09743</td>
</tr>
<tr>
<td>V_r [Reference Velocity, m/s]</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>D [Drag, N]</td>
<td>1.424</td>
<td>2.0166</td>
</tr>
<tr>
<td>L [Lift, N]</td>
<td>-0.00848</td>
<td>-0.442</td>
</tr>
<tr>
<td>C_D [Drag Coefficient]</td>
<td>0.257</td>
<td>0.31</td>
</tr>
<tr>
<td>C_L [Lift Coefficient]</td>
<td>-7.55E-04</td>
<td>-0.068</td>
</tr>
<tr>
<td>M_D [Drag tipping Moment, N·m]</td>
<td>0.197</td>
<td>0.2733</td>
</tr>
<tr>
<td>Stability Margin [%]</td>
<td>77</td>
<td>57</td>
</tr>
</tbody>
</table>
Conclusions

- The present work has to be used to evaluate the stability of HP3 instrument on the Mars surface in present of Martian Dust Devil winds

- The results of CFD analysis has been used to improve and validate an Instrument thermal model

- A CFD analysis simulating the vortex is implemented to show the interaction between Martian dust and the instrument

- A further analysis is using the results of CFD calculation to study the slipping of the feet
Thank you for your attention

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