Tractive performance modelling of the ExoMars Rover wheel design on loosely packed soil using the Coupled Eulerian Lagrangian Finite Element Technique

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• Introduction ESA Exomars Rover wheel design

• Finite Element model of soil-wheel interaction and Eulerian technique

• Constitutive modeling of loosely packed Martian soil

• Simulation Results

• Conclusions
Wheel design was done under severe volume and mass constraints imposed by accommodation of rover in lander / descent module; ESA imposed gradeability (i.e. slope performances) requirements deemed necessary for the rover to perform its mission.

Industrial Contractor has proposed flexible metallic wheels, i.e. wheels with a deformable rim, which provide a bigger contact patch then rigid wheels;

A lower limit to the allowable flexibility was formed by the structural integrity of the wheels, leading to a stiffness value of 13.2 kN/m for an applied radial point load.

diameter=25 cm, width=11.2 cm.
In general vehicle-terrain interaction is a complicated set of phenomena, constituting a three-dimensional, nonlinear, dynamic problem even just at the wheel level.

For performance predictions empirical methods are usually applied, requires in-situ measurements under similar conditions, cannot be applied for predicting performances on Mars.

Conventional terramechanics approach does not adequately model certain effect such as: compressibility, effects of gravity on the soil, terrain slope, wheel design features, layering in the upper soil.

Recent developments: Finite Element Methods (FEM) as well as Discrete Elements Methods (DEM) for wheel-terrain interaction.

Important to account for the deformable nature of both the wheel and the terrain in a fully three-dimensional model.
Wheel-soil interaction FEM model

Program used: DS Simulia ABAQUS FEA

Used solver: Coupled Eulerian Lagrangian (CEL) with explicit time integration

Wheel modelled as Lagrangian Finite Elements (the wheel mesh deforms with deformation of the wheel)

Soil modelled with Eulerian Finite Elements (fixed mesh, material flows through mesh)

CEL technique allows large deformation of the soil under the distortion of the grousers
Wheel-soil interaction FEM method (Wheel Model)

Deformable wheel stiffness matched to 13.2 kN/m under point load on grouser

shell

grousers

Deformable body

Deformable wheel stiffness matched to 13.2 kN/m under point load on grouser
Constitutive soil model (Cap-Hardening)

Simulation, using DPCH soil model, of a triaxial compression test confirmed that soil behaviour is typical of soft, compactive soils, good representation of MCC.
Constitutive soil model (Cap-Hardening)

Soil where wheel has been has a loading history and remembers previous reached stress states.

Soil is compacted and hardened

Previously reached stress state is “remembered” in the form of pre-consolidation pressure

Pre-consolidation stress contours for the compaction and cap hardening

Pristine untraversed soil:

Lower pre-consolidation stress at surface

Higher stress at depth because soil weight leads to higher pressure with depth
1. Initialization ($K_0$ procedure for determination of horizontal stresses, with $K_0 = 0.5$);

2. Soil equilibrium with Martian gravity (small effect after 1.);

3. Wheel indentation: vertical wheel load applied in 10 steps;

4. Wheel driving, at specified speed and slip conditions.
Definition of slip

Assumption: steering angle is zero, no side slip

(longitudinal) **slip:** \( s = 1 - \frac{v}{\omega r} \)

Whereby:
- \( v \) is the wheel’s (and the vehicle’s) translational velocity (m/s),
- \( \omega \) is the wheel’s angular velocity (rad/s),
- \( r \) is the wheel radius (m) (nominal, i.e. undeformed value).

Used values \( v = 0.1 \) m/s, slip: 10, 25, 50, 75 and 95 %.

Translational velocity value has been chosen significantly higher than what is foreseen for the ExoMars Rover for reasons of computational cost, with a negligible effect on the representativeness as effects of mass inertia are negligible compared to interaction forces at these speeds.
Simulation with zero wheel slip
Simulation with zero wheel slip

Soil bumps spacing equal to grouser spacing on wheel
Simulation at 50% slippage
Simulation at 50% slippage

Soil bumps spacing half of grouser spacing on wheel
Simulation at 50% slip results vs time

**Drawbar pull**
- net horizontal force
- tractive force – Σ motion resistances

**Indentation phase**

**Steady state**

Average value in steady state used for comparison of results at different slip degrees

**Start of driving**

**Input torque**
Drawbar pull versus degree of slip, plotted with results for wheel without grousers

- Rigid wheel (⌀=0.25 m)
- Deformable wheel with grousers
- Deformable wheel (⌀=0.25 m)
Input torque versus slip

- Rigid wheel (⌀=0.25 m)
- Deformable wheel with grousers
- Deformable wheel (⌀=0.25 m)
Sinkage in steady state driving versus slip

Grouser wheel does not reach a true steady state at 95% slip, digging into soil for more than wheel axle.
Conclusions (1)

• The Coupled Eulerian Lagrangian method resolves much of the limitations previously inherent to FEM methods. Large deformation of soil under the distorting actions of a wheel with the grousers has been successfully modelled.

• The FEM approach enables the complex behaviour of soil to be modelled, in particular the compaction behaviour of loose packed sand of the Mars.

• The present simulations enable to conclude that for slippage below 15 – 20 %, the differences between the wheel with grousers and without grousers are not significant at this wheel size.

• For higher degrees of slippage, the differences between wheels with and without grousers become apparent and significantly higher drawbar pull can be generated using grousers.
Conclusions (2)

- Experiments on a physical model wheel performed in parallel with the FEM simulations indicate drawbar pull and input torque vs slippage trends that are similar to the simulations.
- At very high slip degrees (here 95%) the grouser wheel digs itself into the ground and does not reach a steady state forward motion any longer.
- The current FEM simulations can be used to calibrate results with physical experiments and study the effect of changes in soil properties on tractive performance. Effects of gravity, slip and slope also can be studies effectively.