ABSTRACT

Tractive performance of wheels on loose fine sand is assessed using state of the art Finite Element Method (FEM) simulations and soil mechanical modelling. These simulations comprise the sand as a continuum with an advanced material model using Eulerian techniques capable of simulating large deformation of sand under distortion by grousers. The wheel model is based on the ExoMars Rover flexible wheel design with grousers and is modelled using Lagrangian techniques.

The computational setup allows for wheel-soil interaction simulations of all kinds of soil, terrain conditions, and wheel designs. In this paper drawbar pull, input torque and sinkage are presented, determined as a function of the degree of slip. Initial comparison with physical tests shows realistic behaviour for the soil deformation and wheel-soil interaction.

1. INTRODUCTION

The dimensions of the wheels of ESA’s ExoMars Rover, planned to be launched in 2018 and to be delivered to the Martian surface by a NASA/JPL lander in the frame of a joint NASA-ESA mission, have been severely constrained by a number of factors, including the overall mass budget for the rover.

In order to meet the gradeabilities (i.e. slope performances) which are deemed necessary for the rover to perform its mission under those constraints, the industrial contractor has proposed flexible metallic wheels, i.e. wheels with a deformable rim, which provide a bigger contact patch with respect to rigid wheels of the same diameter and width. 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. The baseline wheel design used in the late 2009-2010 timeframe is shown in Fig. 1. It has a stiff aluminium hub, in which the drive actuator is accommodated, connected to a sheet metal rim (“tire”) via flexible sheet metal spokes, the load deformation of which is shown in Fig 1 (r).

Two rigid discs with a diameter intermediate between the hub and rim, termed ‘bump stop discs’, limit the wheel deflection to prevent yielding.

The wheel diameter is 250 mm and the width is 112 mm. Twelve grousers (i.e. lugs, cleats) of 9 mm height are mounted on the rim to improve the traction.

2. TRACTIVE PERFORMANCE MODELLING AND ASSESSMENT

In general vehicle-terrain interaction is a complicated set of phenomena, constituting a three-dimensional, nonlinear problem at the wheel level with major consequences for performance. Empirical methods are commonly applied for performance predictions [1][2]. This requires in-situ measurements of the exact soil materials under similar conditions and can not be simply applied for predicting performances in other planetary conditions such as on Mars.

The conventional terramechanics (study of soil properties in relation to locomotion) approach [2] for modeling tractive performances, is based on the modelling by M.G. Bekker and was established in the 1950 and 1960s and developed further by others. It has inherent limitations for the evaluation of the ExoMars rover locomotion performances on Mars, because a number of effects are not taken into account adequately. These effects include the loose, granular nature of the soil, effects of gravity on the soil, terrain slope, wheel design features, wheel motions such as slip and drift, and non-homogeneous, layered, soil including surficial
crusts and hard sub bases.

Considering the limitations of the available mathematical modelling of vehicle-terrain interaction, especially for flexible wheels, the ExoMars project decided in 2009 to specify and verify the rover’s gradeability performances for prototype locomotion subsystem hardware for a set of Martian soil simulants in order to assess the tractive performances experimentally. The simulants were a fine dust, a very fine sand and a gravely medium-to-coarse sand, and tests were performed under typical terrestrial conditions at Mars-representative wheel loads (mass scaled by ideally 0.38% in the tests) The choice of this set of simulants is based upon observations in [3][4][5][6] and is described in [7]. These simulant soils have been specified in terms of constraints on particle size distributions, particle shape and mineral composition. Their procurement happened largely in parallel to the simulation work described here.

The experimental approach facilitates the locomotion subsystem development at this stage. It leaves, however, significant uncertainty about the corresponding gradeabilities on Mars, where effects of gravity differ, and, e.g. where the porosity of some soils may well be higher, compromising the tractive performances. Since these Martian conditions for the soil, in particular effects of gravity on both the nature of the soils and traction, are difficult to test on Earth in a sufficiently wide range of conditions, the use of validated numerical methods is needed for predicting effects on tractive performances.

Numerical wheel-soil interaction simulations complement the laboratory simulations with physical models. It is possible to study a variety of phenomena in a controlled way using numerical simulations, assisting design decisions. Two numerical methods that are widely used for wheel-terrain interaction modeling are the Finite Element Method (FEM) and the Discrete Element Method (DEM). An overview of these methods is given in [2]. An interesting application of DEM is given in [8].

In this paper the FEM approach is taken using the software Abaqus FEA by Dassault Systems' Simulia. The use of Finite Element Methods for modelling wheel-soil interaction has been addressed in various ways in [1][9][10][11][12][13][14][15][16][17][18] and [19]. In these studies, FEM methods similar to the Arbitrary Lagrangian Eulerian (ALE) technique have been applied. The simulations presented in this paper are an extension of this previous work, in that a combination of a flexible wheel with grousers in a three-dimensional model is simulated with slippage. For this the Coupled Eulerian Lagrangian (CEL) approach is used which has recently become available in Abaqus FEA. Here the soil is modelled with Eulerian elements which use a static mesh through which the soil material can move freely under large deformations. This allows the simulation of large deformation of the soil under distortion by grousers, previously only seen in DEM simulations. Together with the advanced constitutive models developed for the simulation in FEM to describe the complex soil behaviour the present FEM approach provides a powerful tool for wheel-terrain interaction simulation.

3. FEM MODEL AND SIMULATION SETUP

3.1. The wheel model

Fig. 2 shows the wheel model which is modelled using Lagrangian elements. The width of the wheel model is half the width of the physical wheel, and a symmetry condition is applied to one side in the simulation.

The wheel has three groups of elements: the body of the wheel, an outer ring of shell elements and the grousers. These three groups are modelled linear elastically with a specific Young's modulus and poisson's ratio. The shell ring ensures that the wheel circumference remains virtually constant during deformation, which is a property of the reference physical wheel. The inner nodes of the body, the nodes at the boundary of the hub, are fixed relative to each other and are tied to a reference node located at the axle of the wheel. Applying rotation and translation to this reference node applies the rotation also to the inner nodes of the body and in this way a rigid wheel hub is modelled. The stiffness of the wheel is matched to the stiffness of the reference wheel (Fig. 1) under application of a point load on a grouser.

3.2. The soil model

The soil is modelled with Eulerian elements, meaning the mesh is static while the soil can move from element to element under the distortion by the wheel and
grousers. This has the advantage that the mesh is not distorted under large deformations, as occurring when a wheel with grousers is ploughing through soil. As soil material is transported through the mesh, elements can become (partly) void in certain situations. This can also happen as a result of soil compaction. The amount of soil material in each element is expressed as a volume fraction which is tracked by Abaqus FEA during the simulation. Elements containing soil take part in the simulation.

Wheel-soil contact can take place in elements when the wheel intersects the soil mesh. If an element of the soil mesh is fully occupied (overlapped) by the wheel it does not contain any soil material. If an element is partly overlapping with the wheel and also contains soil, wheel-soil contact can take place. This contact is handled by a special algorithm which computes the contact forces using user-defined properties, in this case Coulomb friction behaviour with a coefficient of 0.4.

The dimensions of the soil model are 3 x 0.8 x 1.2 m, but only the elements in the lower 1 m are filled with soil initially. This allows soil material to move into the upper, initially empty, elements under the influence of the wheel motion in certain conditions and the terrain surface can develop visible soil bumps. In the simulations presented here the bumps are not pronounced due to the high compressibility of the soil. The model is large enough to avoid influences of the boundaries for the wheel size used. The bottom and the 4 sides of the mesh are closed and the soil material can not displace normal to those planes. The top of the model is a free boundary.

3.3. Constitutive model of the soil

Tractive performance was evaluated for one anticipated type of Martian soil, a loosely packed very fine sand. The morphology of some of the terrains crossed by the Mars rovers Spirit and Opportunity, suggests a substratum composed of such a material, notably wind blown deposits capable of forming distinctive aeolian dune morphology with geometry suggestive of fine sand [7][16]. Pictures taken with the navigation camera of Opportunity on e.g. Sol 823 show ruts of the rover in “dune sand” material, without a thick indurated crust, overlying a hard substratum.

An important characteristic of such a loosely packed very fine sand is that it is highly compactive. The effects of compaction on soil properties are captured in the numerical constitutive model by using Cap Hardening. A cap is a surface in stress space. For stresses within the cap the behaviour is elastic. When stresses reach the cap and are further increased, the behaviour is plastic and soil compacts. The cap itself is then “pushed up” to the newly reached stress levels.

Upon unloading the behaviour is elastic and the soil can be reloaded up to the previous reached stress state before cap plasticity and compaction occur again. Cap models “remember” previously reached stress states by a state variable called pre-consolidation pressure. Fig 3. shows the pre-consolidation pressure contours for a simulation with the wheel rolling without slip.

![Figure 3. Pre-consolidation pressure contours for simulation for a rolling wheel without slip, showing the “memory” of the Cap Hardening model.](image)

In pristine conditions the pre-consolidation pressure increases with depth from blue to red (at and near the boundaries of the model). At the location of the wheel and where it passed, the pre-consolidation stress is higher and soil is compacted in those areas. The soil is mostly being compacted under the wheel load and hardly any soil is pushed sideways, leaving no bumps next to the rut. The rut and absence of pushed-up ridges correspond with that of observed rover tracks on Mars for this type of material showing that the characteristic behaviour can be modelled effectively with Cap Hardening models.

There is a nonlinear relation between the volumetric strain of the compaction and the pre-consolidation stress [18][19]. This is implemented as a user-defined function created for this purpose in the constitutive model. The chosen relation is that of the Critical State soil model [17].

In addition to Cap Hardening, shear failure is modelled with the Drucker Prager plasticity model, which uses a
cone-like yield surface at which soil shear failure takes place. The constitutive model is completed further with elastic behaviour, density and damping as the simulations are performed including the effects of dynamics. The actual set of parameters used is the same as used in the previous ALE simulations and is given in [18] and [19].

3.4. Simulation Setup

For each simulation run the soil model and one of the wheel models are united in one assembly. The wheel is initially positioned just touching the soil surface at a distance of 1/3 of the edge of the soil model in the length direction. The simulation has four stages, similar to what was done in the ALE modelling [18][19]:

1. Initial stage. Here the vertical soil stresses and horizontal soil stresses are initialized using a “K0 procedure”. The vertical stress at a depth of one wheel diameter is determined by the weight of the soil layer above. This value is multiplied by K0 to determine the initial horizontal stress at that depth. The value K0=0.5 has been used here, which is common for normally consolidated sands. The pre-consolidation pressure for the Cap model is initialized, characterizing the loading history of the soil.

2. Equilibrating gravity loads, wherein gravity is turned on for the soil model and Abaqus FEA brings the soil stresses in equilibrium with the gravity load.

3. Wheel indentation. The wheel is kept fixed horizontally and rotationally, while applying a vertical wheel load. The load is applied as a step function from 0 to 86 N (half of the ExoMars rover maximum wheel load of 172 kN at slope of 0°).

4. Wheel Driving. The vertical wheel load is kept constant at 86 kN, and the translational velocity v is ramped up linearly from zero to the nominal value in 0.1 s to have a smooth transition from stand still to motion. The rotation of the wheel without slip is not restrained simulating a free-running wheel. In the cases of nonzero slip, a rotational velocity of the wheel is applied according to \( s = 1 - v / \omega R \), as in [2]. Here the translational velocity \( v \) and wheel radius \( R \) are input, and the angular velocity \( \omega \) is calculated for the degree of slip \( s \) that is required. The driving step is simulated for a time period of around 5 s, enough to reach a steady state in the relevant simulations.

4. SIMULATION RESULTS

Using the setup described in the previous section, simulations have been run for 7 slip degrees, notably: free running, just slipping, 10%, 25%, 50%, 75% and 95% slip.

Fig. 4 shows soil deformation at the end of the simulation with 50% slippage. It can be seen that the distance between the bumps inside the rut is about half the distance between the grousers on the wheel. For zero slip, this distance is equal to the grouser distance. This phenomenon is also experimentally observed for such slip values [21].

The horizontal reaction force, wheel input torque and its vertical displacement versus time are the main output of the simulations, presented here. The values for the steady state are the average of the last second of the simulation. These values are plotted versus the degree of slippage. Fig. 5, 6 and 7 show respectively the drawbar pull, input torque and sinkage in the steady state versus the degree of slippage. Results for a wheel without grousers (flexible and rigid) have also been plotted.

Figure 4. Simulation at 50% slippage.

Figure 5. Drawbar pull versus slippage for the deformable wheel with grousers plotted together with results for a rigid and flexible wheel without grousers.
It can be seen that a wheel with grousers generates significantly more drawbar pull when the degree of slip increases compared to the wheel without grousers in this material. Without grousers the drawbar pull remains almost constant with increasing slip, indicating that the limits of tractive performance are reached abruptly when the motion resistance exceeds a threshold value. This effect is also observed experimentally [21] where it was found to be more pronounced for larger grouser heights of 10 and 15 mm, less so for a grouser height of 5 mm and an almost constant drawbar pull with increasing slip for a grouser height of zero. ESA has indicated that this effect of grousers has also been found in the single wheel test data for the flexible wheel reference design in the tests on the gravely medium-to-coarse sand stimulant, for wheel loads ranging from 70 N to 270 N, which have been performed in the ExoMars industrial team in parallel to this simulation work.

There is also a correspondingly higher input torque with increasing slip for the grouser wheel. Also, the sinkage is much higher for the wheel with grousers, with the increase in slip. The sinkage at 95% slip resulted in the wheel digging itself almost fully into the soil, without arriving at a true steady state as was the case for all other slip degrees.

5. CONCLUSIONS

The interaction of a wheel with grousers with soil, a loose very fine sand, has been studied numerically using the Coupled Eulerian and Lagrangian finite element technique. 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 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. Significantly higher drawbar pull can be generated using grousers. At very high slip degrees (here 95%) the grouser wheel apparently digs itself into the ground and does not reach a steady state forward motion any longer. Soil displacement by grousers is already apparent at much lower degrees of slip however.

The current numerical simulations concern a combination of one soil material and one flexible wheel. The model can be further calibrated by comparing the results of such simulations with physical tests with materials for which the relevant parameters have been determined. Sensitivity studies can then be done numerically for soil materials covering the range of Martian soils to be anticipated and effects of dimensions and flexibility of wheels with small or large grousers and effects of gravity, slip and slope can be studied. Physical tests using selected soil materials and wheel designs provide the necessary model validation.

6. REFERENCES


