WHEEL LEVEL TEST DATA GENERATION AND UTILIZATION TO PREDICT LOCOMOTION PERFORMANCES OF PLANETARY ROVERS AND VALIDATE SIMULATION TOOLS

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ABSTRACT

A major challenge in planetary exploration robotics is to provide increased rover mobility, which is necessary in order to provide access to a wider range of scientific sites, through improved rover locomotion. The wheel is the physical interface between the vehicle and the deformable, granular terrain encountered on Moon or Mars and the only means by which the vehicle can generate the necessary forces for its motion.

Understanding the interaction of small to medium sized rigid and flexible metallic wheels on loose soils is therefore crucial.

In order to validate simulation tools and perform locomotion prediction for planetary exploration rovers, there is a need to have accurate and extensive datasets of representative wheel-soil interactions. To record these datasets, a dedicated facility as well as various wheels and representative soil simulants and conditions are necessary. Post-processing wheel level test data for direct utilization within a rover simulation tool could also be envisaged but due to the large number of data, a more elegant way than look up tables is needed.

This paper presents the overall approach used for wheel testing, summarizes results of the single wheel test programs conducted so far and discusses the required processing for test result import into a universal wheel tractive module.

1. INTRODUCTION

The Single Wheel Testbed (SWT) developed by RUAG Space is based on the extensive experience gained during the ESA RCET [1] and ExoMars LSS activity [2]. Its innovative architecture allows to accurately controlling wheel slip and recording of all the forces and torques that apply at wheel level. In addition, the very low resistive force of the installation allows the accurate determination of traction performance at low or even negative slippage.

A generic application called Wheel Parametric Analytical Tool was developed in order to import and process the experimentally recorded wheel-level performance data (drawbar pull, wheel torque, resistive forces and sinkage vs. slip). The application of polynomial fitting method allows decreasing memory demand compared to pure look-up tables and enables a quick and efficient access to wheel performance data via simple, continuous functions. The function parameters are exported into a “.csv” file with a standardized format that can be loaded by a wheel module (*.dll). Such a module was developed by RUAG Space and demonstrates its capability for predicting the ExoMars LSS Breadboard 2 performances when implemented in a rover level simulation tool as presented in [3]. Different fitting methods were investigated and the accuracy of interpolating / extrapolating wheel performances was verified experimentally. This provides a basis for any future wheel characterization program and generates a significant set of wheel soil parameters. Finally, the required wheel data accuracy necessary for predicting rover performance prediction was analyzed in order to update the specification applicable to single wheel testing.

2. WHEEL METRICS

The relevant soil-wheel interaction values to be measured are the following:

1) Drawbar pull *DP* is the net pulling force in the direction of motion (soil thrust H reduced by motion resistance R) and is given by:

$$DP = \sum_{j=1}^{j=m} (H_j - R_j)$$

With j the number of wheels

This value represents the extra capability of a wheel or rover that can be used to counteract an increase of the motion resistance like the one produced by slopes or obstacles.

2) Input torque *T* is the effective moment applied on the wheel by the drive unit. The peak value is commonly used as sizing case for the actuator and drive electronic. The value at a given operating condition can be

combined with the angular velocity and actuator characteristic in order to determine the required energy.

3) The motion resistance *R* is the resulting force acting in the opposite direction of the motion that in case of a wheel moving on a loose soil is composed of:

$$R = Rc + Rb + Rw + Rg$$

Rc = compaction resistance
Rb = bulldozing resistance
Rw= wheel internal resistance force that include hysteresis (flexible wheel)
Rg = gravitational resistance

4) Sinkage *z* is the amount or degree of sinking. In terramechanics this can be defined as the vertical distance between the non disturbed surface and the bottom of the wheel without grouser (z_0 in Fig. 1). The amount of sinkage depends on the physical properties of soil and dimension, shape, stiffness and loading of the wheel.

Note: all those values are slip dependent and need to be determined for different operating condition (e.g. wheel load, multipass, etc).

5) Slip is defined as follow:

$$slip = (r \cdot \omega - v_X) / (r \cdot \omega)$$

r = wheel radius in [m]
for flexible wheel it is the undeflected wheel radius
ω *= wheel rotational velocity in* $[s^{-1}]$
v_X *= linear velocity in [m/s]*
rover or the sled velocity in the driving direction

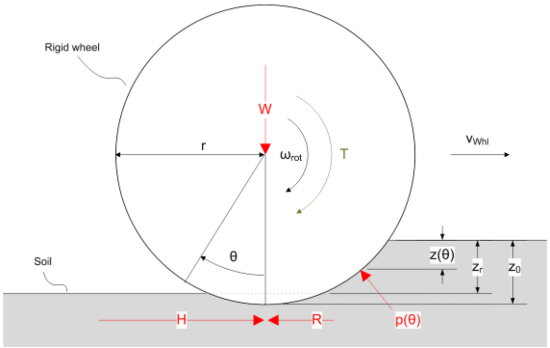

Figure 1. Mechanics of wheel-soil interaction. Forces and pressures are drawn in red, Torques in green.

6) Multipass
- Multipass “0” defines the first wheel run in the undisturbed soil
- Multipass “i” defines the wheel run when i passes were made before

3. SINGLE WHEEL TEST FACILITY

Soil channels are frequently used primarily in the development of terrestrial off-road vehicles. In a soil channel, the wheel in question can be traversed in towed or propelled state while running in a bin filled with a uniform soil. Concurrently, forces, torques and rotation rate are measured which allow to characterize the tractive behaviour in terms of motion resistance, drawbar pull etc as function of wheel slip and wheel load. Soil channels attempt to operate a wheel under controlled loading and controlled soil conditions to obtain reproduceable measurements. This is in contrast to field trials where single wheels or rovers are operated on naturally occurring - and thus inhomogeneous - soils.

3.1. Overview

The RUAG Single Wheel Facility includes the following items:
- The bin filled with the test soil of 6.20x0.70x0.3m
- The sled carrying the single wheel to be tested and the sensors, with the sled moving over the soil bin and the wheel running on the soil surface
- A parallel suspension allowing applying a given vertical load to the test wheel
- The motorised tether (cable) that can be connected to the sled in order to impose a given force or linear velocity

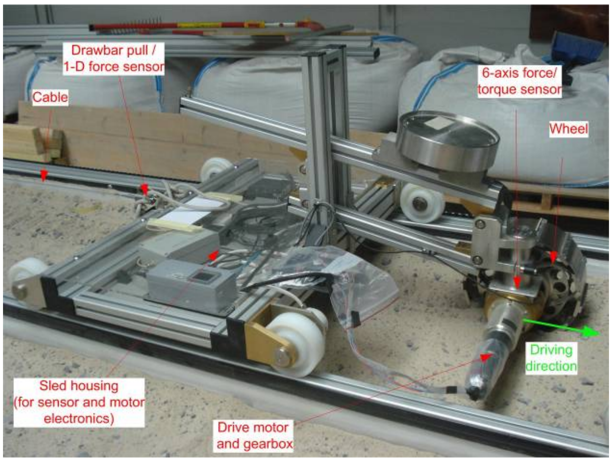

Figure 2. RUAG Single Wheel Testbed (SWT) filled with Martian soil simulant ES-3

The sensors and acquisition units are accommodated on the sled and controlled by a standard PC via USB and Ethernet:
- The Drawbar Pull is measured by a single axis force sensor accommodated on the cable up to 1000N
- The input torque and wheel load is measured by a 6-axis force/torque sensor accommodated on the axis of the wheel
- The wheel angular velocity is measured by the integrated encoders of the motors
- The linear velocity is measured by an encoder

mounted on one of the wheel axis of the sled and by the integrated encoders of the tether motors

- Wheel hub displacement is measured via an angular sensor accommodated on the parallel suspension. The angle is then converted into millimetres. In order to allow relative measurements (i.e. relative to the soil surface), the value is initialised to zero during the calibration phase
- Sinkage for flexible wheel is measured manually with a laser telemeter

3.2. Operation

Thanks to the motorised tether, the facility can work in speed control or in force control mode. Other modes of operation are also available as described in the following.

Force control
Because wheel featuring grousers exert a tractive force with a variation function of the number of grouser in contact with the soil, active force control shows mitigated results. Passive system based on a brake or weights were also investigated but due to the strong linear velocity variation the DP versus slip determination is inaccurate.

Speed control
The speed control mode enables to impose a given wheel slip value and records the dynamic pulling force variation with a high accuracy. The facility controls the wheel rotational velocity with a drive unit, while its linear velocity is controlled via the motorised tether. This solution avoids having unexpected sled slippage and enables setting the required wheel slip to a given value with an accuracy of a few %. Both the tether speed and sled speed are measured with different sensors in order to verify that the effective sled speed correspond to the targeted speed.

Free sled
For determining the minimum slip value, the tether system is disconnected from the sled. The wheel is controlled at a given speed and the resulting linear velocity determined by the sled encoder. For such a measurement it is important that external motion resistive forces like the sled are minimised and constant. This is achieved by using PET wheels rolling on the bin profile in aluminium. Such a solution is not prone to wear or dust sensitive. The fact that the wheel, tether and sled are aligned avoids unexpected lateral forces or bending moment that could produce an increase of the resistive force in particular when high load is applied.

Unpowered wheel
For measuring the wheel motion resistance on loose soil or hard ground, the drive unit is disconnected from the wheel hub and the unpowered wheel pulled by the tether. This mode can also be used in order to test the resistive force of a blocked wheel in order to simulate a failure situation.

Steered wheel
The wheel can be steered w.r.t the motion direction in order to simulate cross-hill performances that include lateral slip or inaccuracies in the rover control system during a manoeuvre.

4. SOIL DEFINITION AND CHARACTERISATION

4.1. Soil Simulants

Determination of representative soil simulants is a complex task. In order to use directly test data for predicting rover behaviour, it is necessary to use soils that will produce similar tractive performances on Earth than the flight model on the targeted planet or the Moon. The first challenge is that the environmental conditions are difficult to be reproduced at reasonable cost during ground testing (e.g. gravity, atmosphere, low temperature, electro-static or magnetic effect). For example Wong in [6] investigates the influence of change in gravity on the soil in interaction with rigid wheels. To consider this effect modification of the applied load is proposed. Such method can unfortunately not be conducted with flight representative flexible wheels because they are designed for a given nominal load.
The second issue is that so far only indirect information about wheel-soil interaction can be gathered from previous Mars missions making difficult to tune soil parameters for having similar performances.

In order to solve this issue, wheel-soil interaction simulation techniques are often used in order to predict the wheel performances during a given mission. This allows performing sensitivity analysis in order to deal with the uncertainty related to the soil parameters. In order to validate such tools or to adapt empirical formulation like in [5] there is a need for having accurate wheel test data performed on well characterised soils. In this case it is necessary to use soil simulants allowing performing in an accurate and reproducible manner the wheel-soil interaction test. However, using representative soil(s) is less critical because adaptation of simulation parameters can be done for flight prediction.
As a function of the mathematical model or tool used, different soil parameters need to be determined with dedicated facilities (e.g. Bevameters, triaxial cell tests, bulk density determination). In addition, the soil needs to be prepared in a defined state and the environment controlled.

4.2. Soil Parameters

ES-3 is a medium coarse dry silica sand RH 28 DRY that was defined in the context of the ESA ExoMars program in order to be representative of one type of Martian soil. It has a bulk density of ~1'700 kg/m^3, other information are given in Tab 1 and Fig 3.

Table 1. ES-3 grain size repartition

Aperture	Cumulative Passing	Cumulative Retained	Retained Each Sieve
Microns	%	%	%
2000	100.0	0.0	0.0
1400	99.9	0.9	0.9
1000	93.5	6.5	5.6
710	76.7	23.3	16.8
500	50.5	49.5	26.2
250	10.9	89.1	39.6
125	1.2	98.8	9.7
125		100.0	1.2

This soil was then mixed with gravels in order to obtain the targeted particle size distribution shown on Fig 3.

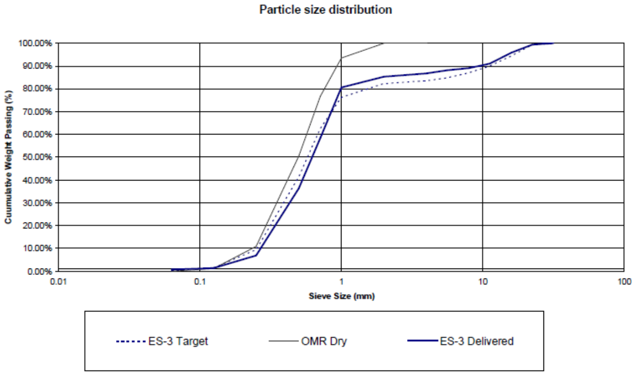

Figure 3. ES-3 particle size distribution including gravel. Cerdit : KIBAG Zentrallabor

5. SINGLE WHEEL TEST RESULT

5.1. ExoMars Flexible Wheel Characterisation

The ExoMars BB2 flexible wheel was developed in the context of the ESA ExoMars Locomotion S/S activity by RUAG Space based on a DLR concept. The main characteristics are reported on Tab.2.

Table 2. BB2 Wheel specification

Parts	Unit	Dimension
Wheel diameter (w/o grousers)	mm	250
Bump stop diameter	mm	200
Wheel width	mm	112
Tyre thickness	mm	0.6
Narrow blade width	mm	25
Narrow blade thickness	mm	0.4
Wide blade width	mm	50
Wide blade thickness	mm	0.4
Number of grousers	-	12
Grouser height	mm	9.2
Weight	kg	1.743

The wheel stiffness was characterised by applying a given force and measuring the displacement as shown on Fig. 4 until the bump stop is reached.

Figure 4. Flexible wheel characterisation bench measuring the stiffness of the ExoMars BB2 wheel

For the targeted nominal load, the stiffness is 11.1 to 15.3 N/mm as a function of the location (i.e. on grouser, between grousers). This stiffness is nearly constant over the full deflexion range. Figure 4 allow to see how the wheel deform under a given load and cross check the model used in the simulation.

5.2. Test data as function of slip

The test performed with the ExoMars BB2 wheel on ES-3 are reported in this section for the minimum, nominal and maximum wheel load (70, 180 and 300N). During those tests the wheel rolling velocity was set to 40 m/h and the values of the "stable" phase of a was run averaged.

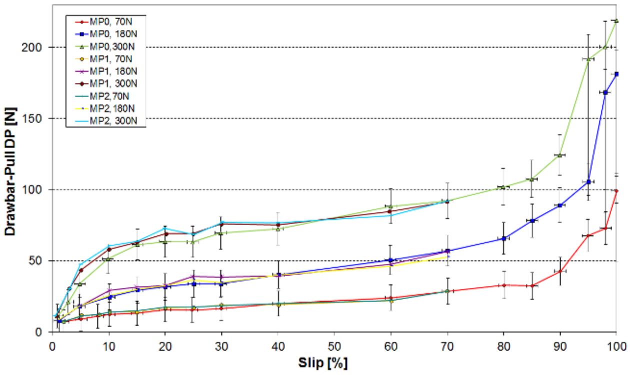

Figure 5. Drawbar pull vs. slip test results. Error bars for multipass case 0 only

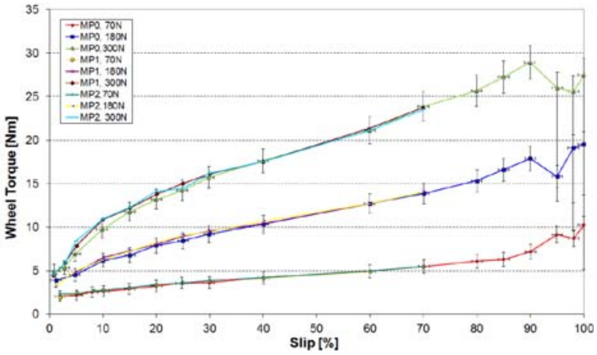

Figure 6. Input torque vs. slip test results. Error bars for multipass case 0 only

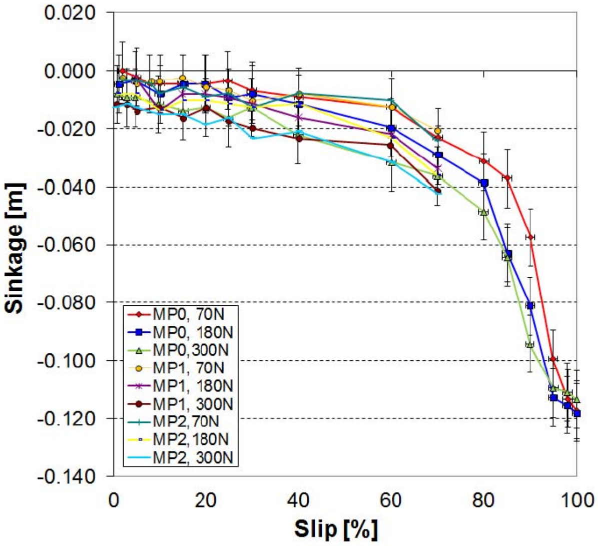

Figure 7. Sinkage vs. slip test results. Error bars for multipass case 0 only

According to the DP equation reported in section 2, the overall motion resistive force on ES-3 can be deduced from the recorded DP, input torque and wheel radius. The result is reported in Fig. 8.

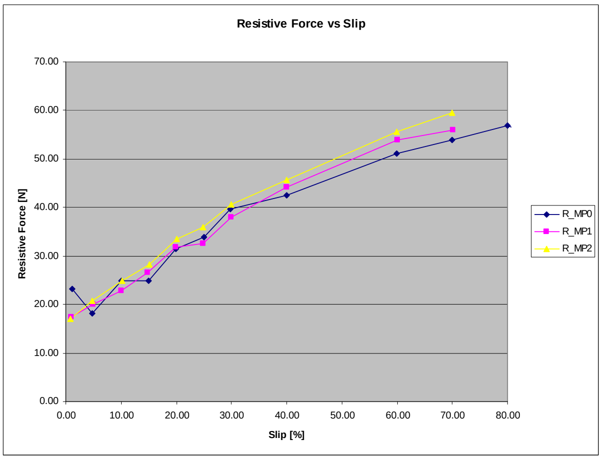

Figure 8. Resitive force vs. slip test results, 180N load

In order to verify this assumption, a test was performed with an unpowered wheel pulled by the tether with same laod. The outcome of it is a motion resistance at near zero slip that correlate well with the values reported on Fig. 8 with 18 to 15 N at MP0 to MP2.

5.3. Analysis of a Test Run

As shown on Fig 9. there is a transient phase of ~25s until the wheel reaches a stable sinkage value. Up to this point, the average value is taken for constructing the plots presented in the previous section. Minor variations of the mean value are due to the presence of gravels in the soil. What is not considered in the previous plots is the significant variation of the drawbar pull and input torque reported on Fig 9. This is due to the number of grousers in interaction with the soil that vary between two and three as shown on Fig 10.

Such a variation is function of load, slip, wheel design and soil characteristic and is very challenging to predict in particular with a semi-empirical approach. Therefore often the average value is used for correlation. If this approach is valid, it has to be noticed that extra capability often exists on real rovers due to this dynamical effect.

Figure 9. ExoMars BB2 wheel input torque and drawbar pull as a function of time, 300N load, 5% slip on ES-3

Figure 10. ExoMars BB2 wheel side view, 300N load, 5% slip on ES-3

5.4. Drawbar Pull Time Dependency

In particular difficult situation like overcoming step shape obstacles, on significant slopes or very lose soils, very high wheel slippage can occurs (i.e. >90%). In this case it was observed a time dependency of the drawbar pull value as shown on Fig. 11. The significant increase of the drawbar pull in the first phase is due to slip sinkage effect and explains that a rover like the ExoMars BB2 takes some time in front of a critical obstacle before being able to overcome it. Because the linear velocity is not sufficient to allow the wheel interfacing fresh soil anymore the drawbar pull drop drastically and remain low as long as the rover is continuing its motion in the same direction. The removed soil is cumulated at the rear creating a positive rut depth as shown on Fig 13 and reducing further the wheel tractive capability.

Such a test is useful in order to increase prediction accuracy on difficult terrain and can be used by mission control or the navigation system in order to define a time limit within which high slippage is allowed.

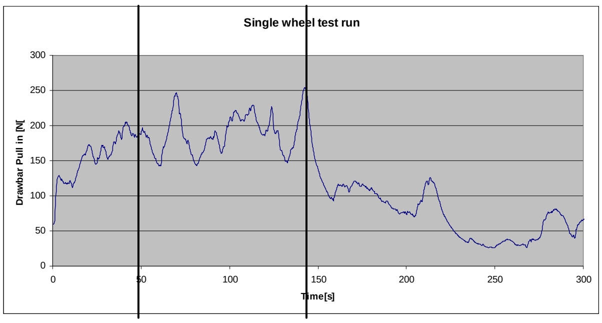

Figure 11. Variation of the drawbar pull as a function of time, 180N load, 98% slip

Figure 12. ExoMars BB2 wheel test at 300N load, 70% slip on ES-3

6. WHEEL SIMULATION MODULE

6.1. Test Program Definition

A significant number of single wheel level tests are necessary in order to determine the metrics versus slip. For having a full characterisation, this needs to be done on various soils, multipass level and load conditions as shown on Fig. 14. In addition, the influences of translational velocity or variation in soil relative density also need to be investigated in order to develop an accurate wheel-soil interaction model.

In order to understand the influence of individual contributor to the motion performance, the full test program needs to be repeated with wheels of various sizes, grousers and stiffness. In this case, an appropriate approach is necessary in order to reduce as much as possible the number of test to be performed.

An intensive work was conducted at RUAG Space in order to develop interpolation techniques allowing providing accurate test data in an indirect way.

The result of it is that, on ES-3, the influence or interpolation error for a given load can be kept to a minimum by employing an accurate 7th-degree polynomial approximation. An interpolation for various wheel loads is also implemented allowing reducing the test campaign to the minimum, nominal and maximum load case only. Data extrapolation is also feasible but produces less accurate results.

This approach was validated by comparing the result of test data at a wheel load of 120N with the data interpolation based on the measured load test as shown on Fig 13.

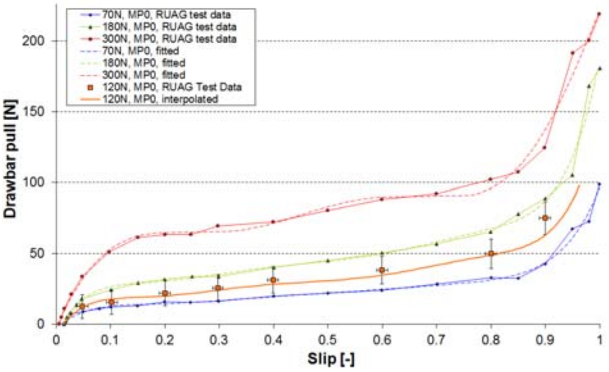

Figure 13. The interpolated DP vs. slip curve in comparison with the test data recovered for a load of 120N (BB2 wheel on ES-3)

This method allows reducing the number of wheel load to be tested down to three. Moreover, once the curvature is now for the nominal load, less slip values are necessary for the two extreme load cases. The influence of multipass effect is also predictable in relation to the motion of undisturbed soil and does not need to be determined for each slip case.

6.2. Architecture

The data interpolation allow to reduce the large amount of test data in a condense form that can be used by a wheel-soil interaction module in order to use directly test data within a simulation tool.

This Wheel Performance Module (WPM) was developed by RUAG Space and successfully integrated in a rover simulation environment [3]. The WPM is a flexible dynamic link library (.DLL) module that acts as an interface for rover-level simulation tools to obtain precise wheel performance data with very low computing resource. This is advantageous in term of simulation time and can be embedded on flight models.

Once the curve is interpolated for the desired load, the WPM generates the curve values over the entire slip range, iteratively searches for the DP, torque, sinkage or resistive force in the curve and then finally returns the corresponding slip. If the required DP is found to be too high, e.g. it cannot be generated by the wheel even at 100% slip, then the WPM returns 100% slip and the maximum achievable DP.

6.3. Input Data Generation

The input data required by the WPM are directly generated by the single wheel application at the end of a test program. Discrete data points are taken, e.g. a number of drawbar pull, torque, sinkage or resistive force vs. slip curves at a certain load and multipass level. A least-squares polynomial curve fit is computed to obtain a continuous function. The degree and thus the accuracy of fitting can be specified by the user.

$$
\begin{aligned}
DP(slip)\Big|_{(Soil,MP,Load)=const} &= \sum_{i=0}^{n} a_{i,DP,Soil,MP,Load} \cdot slip^{i} \\
T(slip)\Big|_{(Soil,MP,Load)=const} &= \sum_{i=0}^{n} a_{i,T,Soil,MP,Load} \cdot slip^{i} \\
\ldots\ .
\end{aligned}
$$

The quantities are the curve parameters for a curve at a certain soil, multipass and load combination. It is shown that depending on the data to fit, polynomials of degrees n = 3…7 provide adequate results.

The method decreases memory demand compared to a pure look-up table and enables a quick and efficient access to wheel performance data via simple, continuous functions. The function parameters are exported into a csv file with a standardized format.

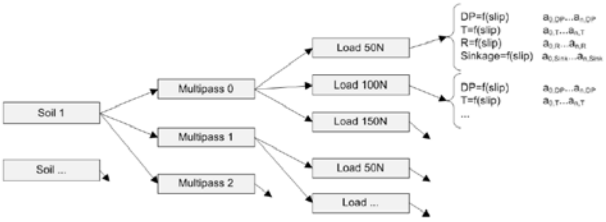

Figure 14. The structure of the fitted wheel performance data as saved in the .csv file.

6.4. Wheel Performance Module Implementation

The WPM can be implemented in every rover simulation environment that is compatible with wheel level inputs/outputs. The main challenge is to be able to reconstruct the rover motion based on wheel level data. A possible approach on this subject is given in [3] and [4]. Simulation on different soils or wheels is easily managed though the csv input files. Those files can also be generated by a validated wheel-soil interaction module allowing switching between wheel test data and simulation.

7. LESSON LEARNED

7.1. Data Accuracy

The data accuracy is not only related to sensor accuracy but also on soil homogeneity and testing approach. Having a single wheel test facility controlling accurately the slip value was found to be the most appropriate way for producing the required wheel-soil interaction data. A motorised tether is not sensitive to dust or wear like a powered sled system moving on a rail. However the cable needs to be bend and thus a minimum draw bar pull is required. Such approach is sensitive to the sled motion resistance that needs to be characterised and minimised by cleaning the rail before the test.

Accommodating the wheel on the middle of the sled via a parallel suspension minimise internal forces that affect sensor accuracy and allow performing test at high loads.

7.2. Test at Low Slip Value

High accuracy in particular at low slip value is required for predicting the rover behaviour on loose soils. To do so, operation with an unpowered sled produces the best result. Determination of the wheel-soil interaction with negative slippage and interpolation is also a way to determine the motion performance at near zero slip.

Slip measurement for relatively low values can also be determined from the wheel track. Given the wheel radius *r* and the number of equally spaced grouser *n*, one can determine the theoretical distance *d* between the grousers by:

$$d = \frac{2\pi r}{n}$$

By counting the actual number of grouser marks in the wheel track over a certain distance, one can then determine the real grouser distance in the wheel track and thus retrieve the slip. This method is very precise because it is only subject to distance measurement errors which can be decreased by measuring over high distances. It was verified that the difference between the manual method and the test facility recorded data lies below 1%. This mean such a method can be used during operation on a planet based solely on the picture of the wheel track (assuming the grousers trace is visible).

7.3. Data Processing

Data processing can be very time consuming. Post-processing effort can be minimised by calibrating each sensor so that it provides directly the value in the required unit.

Using a database allow full traceability between measured values, test conditions and set data. By using data filtering technique, interpolation algorithms and detection of the “stable” phase of a test, the post-processed data are automatically generated by the application for every load and slip combination. This capability can be combined with wheel-interaction models in order to be able to correlate in a user friendly way a simulation tool.

8. Wheel Deformation

Determining sinkage of flexible wheel is not trivial and so far time consuming manual measurement is performed. Combining wheel hub displacement with wheel stiffness characterisation provides accurate results on a relatively low compressive soil like ES-3. However because wheel can deform in a different way on loose soils, it has to be expected that such an approach would need to be verified on case by case.

Wheel deformation introduces a motion resistive force and is less energy efficient than rigid wheels. In order to measure this effect, a test was performed on hard surface adapted to the tested wheel with grousers and compared to the resistive force on soil ES-3 (reported on Fig. 8). This test demonstrates that the impact of wheel deformation is in the order of 4.6N (0.6Nm) that correspond to 25% of the overall resistive force at near zero slip.

9. CONCLUSION

The single wheel testing facility built up at RUAG Space is presented as well as the necessary metrics to be used to characterise wheel-soil interaction. In order to produce accurate test data appropriate design, sensors selection, operating mode and soil preparation is required. Controlling the wheel slip and recording the force and torque produce the most accurate results. For low slip value, using an unpowered sled is more appropriate or interpolation with negative slip test.

A test program conducted with a flight representative wheel on a Martian soil simulant ES-3 allow to validate the facility and the interpolation approach used in order to reduce the number of tests required for characterising a wheel.

This technique implemented in a dynamic link library allows having a wheel-soil interaction module based on test data that can be used by rover level simulation tools in a computer efficient way. This minimises significantly the simulation time and due to the low resource usage can even be embedded on flight models.

In conclusion, by combining interpolation techniques and knowledge of wheel-soil interaction at nominal load, the test program can be significantly optimised and data used for correlating wheel-soil interaction model or directly used for predicting motion performances of planetary exploration rovers.

10. ACKNOWLEDGEMENTS

The wheel and soil used in this paper were developed at RUAG Space in the context of the ExoMars LSS contract. The ExoMars project, within which RUAG is responsible for the Locomotion Subsystem, Astrium Ltd is responsible for the Rover Vehicle and Thales Alenia Space Italy is the overall mission prime contractor to ESA.

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