A Model-Based Parameter Estimation Algorithm for Tire-Soft Soil Contact Model from Off-Road Longitudinal Tests

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A model-based parameter estimation algorithm for tire-soft soil contact model from off-road longitudinal tests

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Abstract. Virtual simulation of wheeled and tracked vehicles on soft terrain is progressively assuming a central role in the design and validation of vehicles, especially for planetary missions, agriculture, and military framework. Over the years, various approaches have been developed for studying the off-road locomotion with different levels of detail, fundamental assumptions, and computational time. On the other hand, the objective measurement of parameters underlying the interaction between soil and wheel is still a challenging task. The goal of this research work is to develop a model-based estimator capable of identifying tire-soft soil parameter for semi-empirical contact models using vehicle measurements. An experimental campaign is conducted to gather wheel torques and angular velocities while driving straight-forward on a sandy terrain. The experimental campaign for validating the contact model and the parameter estimator is conducted on a flat sandy playground using a B-SUV vehicle in All-Wheel Drive (AWD) locked mode.
The experimental test consists of wide-open throttle (WOT) accelerations A 5 Degrees Of Freedom (DOF) virtual vehicle equipped with semi-empirical wheel contact model and fed with the experimental wheel torques is exploited for simulating the real longitudinal maneuvers. An optimization process aiming at minimizing the difference between experimental and numerical wheel angular velocities is defined to tune the main contact parameters. Two distinct experimental data sets are integrated in the optimization loop for pursuing a better estimation. Finally, the algorithm and the contact model are validated through a different experimental dataset.

Keywords: Off-road mobility, tire-soft soil interaction, vehicle dynamics simulation, parameters estimation, optimization algorithm

1 Introduction

The locomotion of wheeled vehicles on a non-rigid surface (e.g., loam, sand, snow) has always constituted a crucial aspect in design and testing off-road vehicle applications. In recent years, planetary expeditions on unknown terrain and army locomotion with heavy and sophisticated vehicle have given a boost in this research area [1, 2]. Modelling the interaction between a moving tire and a soft soil constitutes the first challenging task in terramechanics science, for assessing vehicle performance. To achieve this goal, different approaches have been developed through the years to simulate the mechanical behavior of a soil in relation to a moving vehicle [3] (i.e. empirical methods [4, 5], physical modelling [6, 7] and semi-empirical formulations [8, 9]).

The category of semi-empirical contact models is based on empirical and analytical equations. Several formulations have been proposed through the years for simplifying the contact phenomena [10]. The strength of this approach is the capability of being integrated in custom or commercial software for analyzing the vehicle behavior in off-road conditions. Moreover, they are characterized by reduced computational time thus allowing real-time simulation [11]. On the other hand, contact parameters to be included in semi-empirical models requires relevant efforts for preparing and testing the terrain with time consuming experiments and specific tools [12, 13]. To overcome this issue, some research work dealing with the terrain classification by means of on-board measurements and learning algorithms for planetary exploration [14, 15].

The objective of this research activity is to develop a model-based algorithm capable of estimating the tire-soft soil contact parameters to be used in semi-empirical off-road tire contact models. This estimator relies on an optimization process driven by experimental measurements acquired in real off-road scenarios involving the longitudinal dynamics of the vehicle.

This research work represents the second step of a collaboration with Stellantis OEM group whose main goal is to extend the current testing methodology based on dynamic driving simulators from on-road to off-road scenarios. In the first phase of the project, a custom tire-soft soil contact model based on empirical and analytical equations has been developed in Matlab/Simulink environment. The model was presented in [16] showing the effect of different driveline layouts in longitudinal and lateral handling maneuvers on a clayey terrain.

The paper is organized as follows. First, the contact model between the tire and the soft soil and is introduced, highlighting the main hypotheses and features based on this physical approach. Then, the workflow followed for estimating the soil contact parameters is described. Afterwards, some results are presented for validating both the contact model and the estimation algorithm. Finally, the conclusions of the research work are drawn.

2 Tire-soft soil contact model

In this section, an overview on the contact model between the tire and the soft soil is given. A detailed description of the physical approach has been already presented in [16]. The target of the abovementioned model is to reproduce forces and moments applied to the wheel hub and generated at the interface between a deformable tire and a fine-grained soft playground. The soil surface is assumed flat and characterized by homogeneous properties while the spin axis of the wheel is always considered parallel to the undisturbed soil plane. The multi-pass effect, i.e., the soil plastic residual deformation due to the multiple passage of the wheel (multi-pass effect) and soil damping are not accounted in the model [17].

Fig. 1 shows a sketch of the contact model (on the left) and a qualitative representation of the stress distributions (on the right). Wheel kinematics, vertical load and soil parameters are inputs of the model. Left subplot of Fig. 1 represents a tire (undeformed radius equal to R_t) rotating around the y axis at angular velocity ω and moving forward with velocity V along the x axis. The carving of the tread is neglected while the radial flexibility of the tire is accounted through the approximated circle substitution method [18]. The radius $R^{\star}$ is used to represent the effective contact arc (solid blue line in the subplot of Fig. 1).

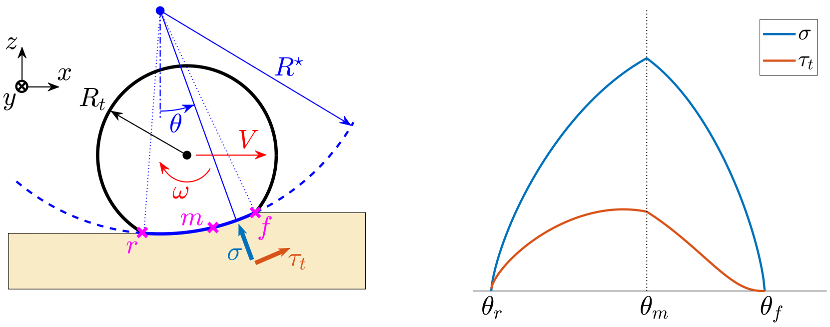

Fig. 1. Sketch of the tire-soft soil contact model (on the left) and qualitative representation of the stress distributions at the contact (on the right)

The contact normal (σ) and the tangential (τ_t) stresses are evaluated as a function of the angular coordinate θ: they are assumed constant along the width of the tire. Some relevant contact points are f and r, i.e., the contact entry and exit points respectively and m, the point where the maximum normal stress occurs. The normal stress distribution (blue line of the right subplot of Fig. 1) is obtained combining Bekker's pressure-sinkage relationship [19] with some experimental evidence on normal stress distribution of rotating cylindrical geometries on a soft ground [20]: it depends on the wheel sinkage through the soil sinkage modulus K_s and the soil exponent n [10]. The tangential stress distribution τ_t (red line in the right subplot of Fig. 1) is evaluated combining the Mohr-Coulomb failure criterion and Janosi formulations [21]: it depends on the normal stress σ, the soil cohesion c and the angle of internal shearing resistance of the soil ϕ, the relative displacement of the tire with respect to the ground j_t and the tangential shear modulus K_t. The longitudinal force F_x, the vertical force F_z and the resisting moment M_y exerted by the terrain on the wheel, are evaluated by projecting the components of the stresses σ and τ_t along the x and z wheel local axes and integrating on the contact patch. The transient behavior of F_x and M_y is accounted for using the relaxation length approach [22].

3 Soil parameter estimation workflow

The developed soil parameter estimator relies on an optimization process based on vehicle simulation and experimental data. This section focuses on the presentation of the algorithm workflow, the experimental campaign for collecting on-board measurements and the development of the virtual vehicle model.

3.1 Workflow

The implemented algorithm for soil contact parameter estimation is shown in Fig. 2. The experimental data signals are used as model inputs (torque) for the virtual vehicle and as benchmark for the numerical results (wheel angular velocities). The nominal values of the soil parameters together with their range of variation are selected combining some experimental evidence (e.g., soil composition, granulometry, compactness, humidity, etc.) with data available in the literature [10, 12]. The simulation run is handled by a constrained multivariable optimization algorithm (fmincon), which operates with a user-defined objective function that minimizes the error between the numerical and the experimental results. The final outputs of the estimator are the soil contact parameters for semi-empirical tire-soft soil contact model.

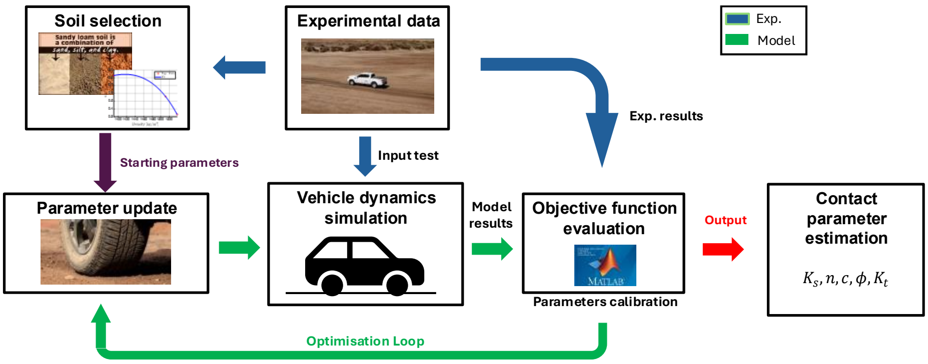

Fig. 2. Soil parameter estimation workflow.

3.2 Experimental off-road testing

The experimental campaign for validating the contact model and the parameter estimator is conducted on a flat playground mainly constituted by sand. The vehicle used for the off-road tests belongs to B-SUV segment. The overall mass (m) of the vehicle is equal to 1797 kg while the tires size is 215/65R17. During the tests, the vehicle operates in All-Wheel Drive (AWD) locked configuration.

The experimental test consists of wide-open throttle (WOT) accelerations starting from standstill conditions. The driver does not give any steering input so that the vehicle can maintain almost a straight-line trajectory. During the tests, the wheel angular velocities (ω_{FL}, ω_{FR}, ω_{RL}, ω_{RR}) and the torque transmitted by one of the rear half shafts ($T_{d,R}$)

are recorded. The maneuver is repeated several times to collect different dataset for the estimation and the validation. Experimental signals are resampled at the frequency of 100 Hz.

3.3 Torque-based vehicle model

The vehicle model integrated in the estimator is characterized by 5 DOFs: a translational DOF for the vehicle rigid body in the longitudinal direction and four independent DOFs corresponding to the angular velocities of the four wheels. The main assumptions underlying the model are reported in the following. The translation in the lateral and vertical direction (along y and z axes) and the three angular motions (around x, y and z axes) of the car are neglected; therefore, the vehicle longitudinal motion along x axis is constituted by the balance of driving forces $F_{x,i}$ (computed from the contact model) and aerodynamic resistances (Eq. 1), where i is used to indicate the contribution of each wheel, m is the vehicle mass, a_x is the longitudinal acceleration, V is the vehicle longitudinal speed and B is the constant drag coefficient. The suspension kinematics is not included in the model. The wheel rotational dynamics is considered by computing with the Eq. 2 the torque balance between the input torque $T_{d,i}$ and the rolling resistance moment $M_{y,i}$, evaluated by the contact model (section 2). J_w is the wheel rotational inertia, $\dot{\omega}_i$ is the wheel angular acceleration. The longitudinal load transfer between front and rear axle is considered and reported in Eq. 3, where g is the gravity acceleration, h_{COG} is the center of gravity height, a and b are the front and rear axle distance from CoG, respectively and L is the vehicle wheelbase.
The input of the numerical model is the experimental driving torque applied to each wheel: hence, the powertrain and the driveline are not modelled. The vehicle under test operates in AWD locked mode. $T_{d,R}$ is directly used as torque input for the rear wheels, whereas it is dynamically scaled for the front wheels according to the front and rear vertical load distribution ($F_{z,i}$), as reported (Eqs. 3 and 4). Load distribution between left and right sides of the vehicle is assumed symmetric.

$$ma_x = \sum_{i=1}^{4} F_{x,i} - BV^2 \tag{1}$$

$$J_w \dot{\omega}_i = T_{d,i} - M_{y,i} \tag{2}$$

$$\begin{cases} F_{z,FL} = F_{z,FR} = \frac{b}{L} mg - ma_x \frac{h_{\mathrm{CoG}}}{L} \\ F_{z,RL} = F_{z,RR} = \frac{a}{L} mg + ma_x \frac{h_{\mathrm{CoG}}}{L} \end{cases} \tag{3}$$

$$\begin{cases} T_{d,FL} = T_{d,FR} = T_{d,R} \frac{F_{z,FL}+F_{z,FR}}{F_{z,RL}+F_{z,RR}} \\ T_{d,RL} = T_{d,RR} = T_{d,R} \end{cases} \tag{4}$$

4 Estimation and validation results

4.1 Estimation through optimization process

The optimization process aims at minimizing the Root Mean Square Error (RMSE) e_i between experimental ($\omega_{k,e}$) and numerical ($\omega_{k,m}$) wheel angular velocities. The general optimization problem is formulated by searching for the optimal variables $\mathbf{x}_{opt}$ which minimize the cost function $C(\mathbf{x})$ reported in Eq. 5, satisfying the lower and upper bounds represented by $\underline{\mathbf{x}}$ and $\overline{\mathbf{x}}$,

$$\begin{cases} C(\mathbf{x}) = \frac{100}{N}\sum_{i=1}^{N} e_i\,(\mathbf{x}) \\ e_i = \sum_{j=1}^{4}\sqrt{\frac{1}{M}\sum_{k=1}^{M}\left|\frac{\omega_{k,m}-\omega_{k,e}}{\omega_{k,e}}\right|^2} \end{cases} \tag{5}$$

where i is the index of the experimental dataset used for the estimation, N is the total number of datasets used for the estimation, j is the wheel counter and k identifies a sample in the time-history array having length M. The selected set $\mathbf{x}$ are represented by the soil contact parameters mentioned in section 2 and reported in Table 1. Nominal values ($\mathbf{x}_{nom}$) refers to LETE sand while the optimization boundaries ($\underline{\mathbf{x}}$ and $\overline{\mathbf{x}}$) are selected to ensure physical range of variation [10]. Fmincon algorithm is selected to solve the optimization problem limiting the maximum number of iterations to 100, the minimum step tolerance to 10^{-3} and the minimum function tolerance to 10^{-3}. Two different experimental datasets ($N = 2$) are used. The initial and final values are listed in Table 1. The optimization algorithm converges in 10 iterations at a minimum value of 8.65%. The estimated final soil parameters show small differences compared to the nominal values, except for parameter K_s, which is much smaller: the change of this parameter causes the wheels to sink more into the soil.

Table 1. Nominal and optimal soil parameter values

Soil parameter	*Nominal value*		*Range*
	$\mathbf{x}_\mathrm{n}$	$\mathbf{x}_\mathrm{o}$	
K_s [kN/m]	535.3	357.6	$\pm$46%
n [-]	0.71	0.71	$\pm$14%
c [Pa]	1150	1150	$\pm$31%
ϕ [°]	31.5	31.5	$\pm$22%
K_t [m]	0.036	0.036	$\pm$41%

4.2 Validation

The optimal set of parameters $\mathbf{x}_\mathrm{o}$ is used for the validation of the entire methodology exploiting a new experimental dataset. Fig. 3 shows the comparison in terms of wheel angular velocities between experiments and simulations. The orange and yellow curves refer to the numerical results obtained with nominal ($\mathbf{x}_\mathrm{n}$) and optimized ($\mathbf{x}_\mathrm{o}$) soil data respectively, whereas the blue curve represents the experimental signals. The nominal soil parameters overestimate the wheel angular velocities with a RMSE of about 43%, whereas the optimized values show a good match with the experimental trend, at each corner, with a RMSE of about 12%.

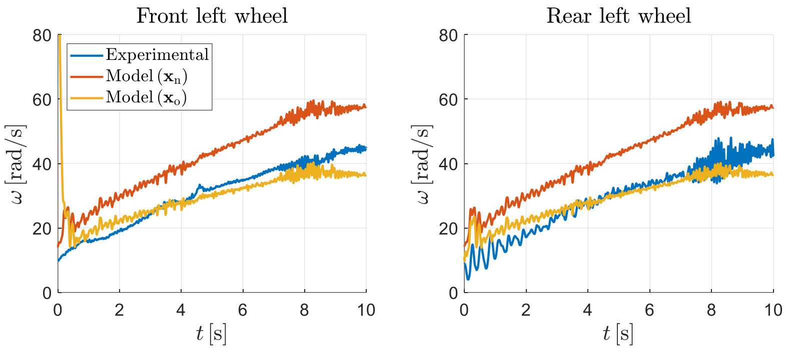

Fig. 3. Experimental-numerical comparison of front left and rear left angular wheel velocities

5 Conclusions

In this research work, a model-based estimation algorithm for tire-soft soil contact parameters is presented. The estimator relies on both experimental and numerical results. The latter are provided by adopting a simplified vehicle model which includes an off-road tire contact model. The optimization loop is based on the minimization of the difference between the numerical and experimental wheel velocities. The results of the entire workflow (optimization and validation) show the following aspects.

- The developed estimator allows obtaining a good match between the numerical and experimental results;
- The parameter which mostly impacts on experimental-numerical matching is the sinkage modulus whereas the numerical variation of the optimized values of the other parameters is minimal. Therefore, the initial parametrization of the chosen soil (i.e., Lete sand) is very close to the experimental playground soil, except for the pressure-sinkage modulus.

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