High-Speed Tyre-Soil Interaction of Aircraft on Soft Runways

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ABSTRACT

A fundamental requirement of military transport aircraft is the ability to manoeuvre on soft soil runways whereby the flotation depends on the aircraft/ runway strength relationship. One must take into consideration that when operating on substandard airfields take-off distance is increasing and extra propulsive force must be available. Hence predictions for the manoeuvrability, the higher rolling resistance compared to rigid surfaces, not to mention the runway damage should be available. These effects depend essentially on the deformation of soil in contrast to rigid pavements where the rolling resistance is caused mainly by internal hysteresis losses in the tyre.

In the design process of concurrent engineering MBS (Multibody System) simulation tools take an important place. In contrast to the CBR (California Bearing Ratio) method, which is until now state-of-the-art in the landing gear design process for soft soil runways, multibody simulation allows to investigate the dynamic behaviour of the vehicle, tyre and soil system. The simulation of tyre-soil interaction by means of multibody tools makes use of analytical modelling and specific measurable parameters are used to describe the physical soil behaviour. With analytical approaches for the tyre-soil contact area it is possible to reach quite a good approximation for the real contact conditions. The main problems in describing the physical soil behaviour are its non-deterministic properties what gives the simulation results, independent from the modelling approach, in terramechanics always quite a great deviation from measurable results.

Other approaches treat the problem of tyre-soil interaction with the method of finite elements (FE) [8][18][26]. These finite element models are of very fine discretisation and allow a precise simulation of the deformations of either tyre or soil but this modelling approach generally needs a large amount of computation time. From this follows a great advantage of MBS simulation in contrast to FE models that a less detailed model setup is required and MBS models can be calculated on commonly used computer systems in a time range of minutes. For this reason MBS is very interesting for extensive parameter variations. In addition MBS simulation allows the consideration of the dynamic interaction of aircraft undercarriage and soil and the fuselage can be optionally implemented as flexible body.

1.0 INTRODUCTION

CAE (Computer Aided Engineering) methods are widely used for investigations of vehicle dynamics on rigid roads and are very interesting for the assistance in the conceptual design phase with the great aim to reduce the amount of needed prototypes for vehicle testing purposes. The problem of measurements gets even worse for aircraft operations on substandard airfields, because in most instances these in-the-field tests are very complex and due to the medium of natural soil mainly not exactly reproducible.

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In the field of contact mechanics of tyres and roads the tyre is considered as elastic body, whereby the simplest model would be a damper and a spring, and the road is mostly considered as rigid surface. The area of terramechanics, which treats the interaction of tyres with soft soil surfaces, is still just a small part in the overall research efforts of tyre contact mechanics. In opposite to the contact mechanics of tyres on rigid roads the premiere model approach for tyres on soft soil would be a rigid tyre and a plastic soil surface. Quite a good survey of this topic is given by Knothe in [14].

The rolling resistance of a tyre on soft soil consists basically of soil compaction, the bulldozing effect, displacement of soil particles and side wall friction. The bulldozing effect occurs quite often when a special combination of tyre, soil and velocity is met and can be illustrated by a bow wave of soil particles which are moved in front of the rolling tyre (shown in Figure 10).

In Figure 1 a survey of simulation methods and gained results by means of MBS (Multibody System) and FEM (Finite Element Method) is given. The rheological soil model with characteristic parameters is used in combination with a MBS description of landing gear and fuselage with the possibility of modelling the fuselage as rigid or flexible body. The formulation of a FE (Finite Element) model makes use of the Drucker-Prager soil model.

The dynamic rolling resistance and tyre sinkage with the interaction of the aircraft landing gear is a result of the MBS simulation. The FE method additionally calculates the tyre and soil deformations, that are caused by soil movement and the bulldozing effect, and therefore makes it possible to achieve better approximations for dynamic tyre-soil interaction.

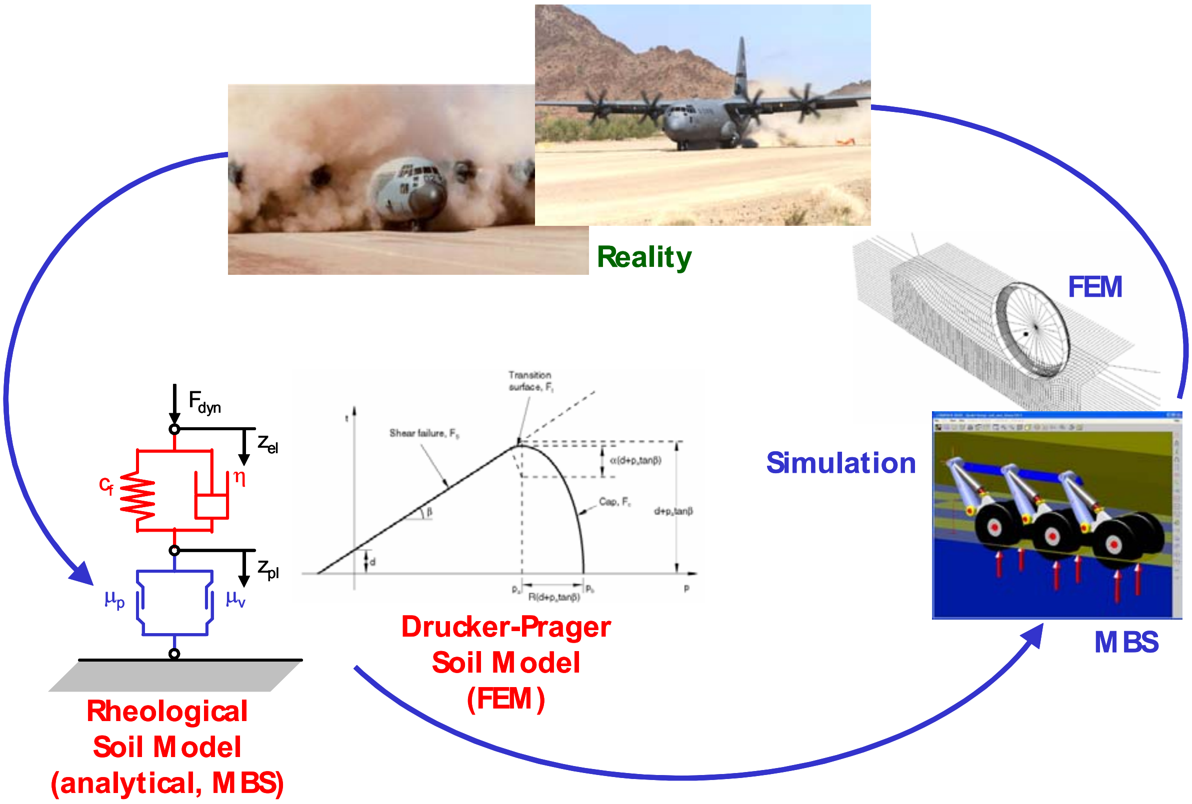

Figure 1: Overview of methods for tyre-soil simulation

1.1 Description of Multibody System (MBS)

A multibody system consists of rigid bodies of specific weight with forces and torques acting on these bodies. The forces and torques are based upon springs, dampers and actuators as well as rigid joints and other bearings [24]. Figure 2 depicts a simple MBS structure with its basic elements. Software tools for MBS simulation are especially used for vehicle dynamic analysis with the following important fields of application [15]:

- tyre-road interaction
- investigation of specific driving manoeuvres
- comfort relevant investigations
- driving performance analysis

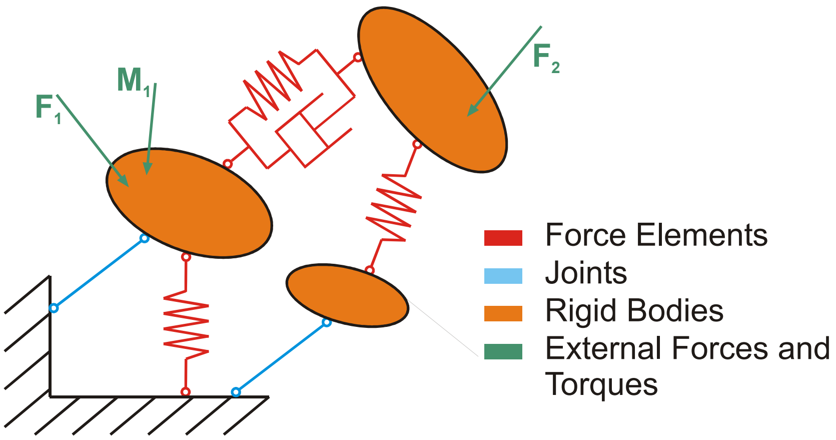

Figure 2: Simple Structure of a Multibody System

1.2 Description of Finite Element Method (FEM)

The theories of Ritz and Galerkin can be assumed as precursors of the method of finite elements [19]. Further development made it possible to transfer these theories onto digital computers, especially by Zienkiewicz [28], so that it is now feasible to approximate solutions of the displacement and deformation conditions of complex bodies. A fundamental disadvantage of the theories of Ritz and Galerkin is that the displacement components have to be applied to the entire body so that for complex situations it isn't possible any more to specify this approach. The finite element method eliminates this disadvantage by separating the geometry of the considered body into sufficient finite parts.

Therefore the advantage of FEM to MBS is the possibility to consider plastic and elastic deformations whereby the MBS formalism allows only the global movement of bodies with the exception of the possibility of integration of elastic bodies in currently available MBS codes.

The Drucker-Prager material law is commonly used for finite element applications in the area of terramechanics [7]. The advantage of the Drucker-Prager approach compared with the Mohr-Coulomb approach is that the first one is continuously differentiable over the yielding surface and therefore it is easier to implement the Drucker-Prager material law into numerical algorithms. An example of a FEM result is given in Figure 3 with a plate sinkage simulation with the Drucker-Prager material law.

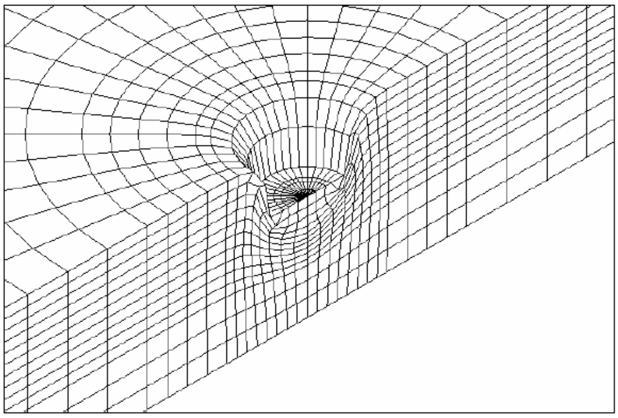

Figure 3: Plate sinkage simulation with the Drucker-Prager cap material model [26]

2.0 TYRE-SOIL INTERACTION

State-of-the-art in the undercarriage design process of current military transport aircraft is the CBR (California Bearing Ratio) design method [4][5]. Wherein the California Bearing Ratio is a measured term of the modulus of subgrade/soil strength. It is the bearing strength ratio of a given soil sample compared to that of crashed lime stone gravel with typical values for CBR of 6-9 when considering soft soil airfields and with a CBR value of 4 for the lowest strength of runways on which heavy aircraft can operate effectively. Figure 4 shows typical CBR values of different soils. Other parameters to be considered for the CBR design method, are the geometry of the undercarriage, the number of tyres and the size of tyres. The result of the CBR design method is the number of possible runway passes with a specific undercarriage geometry on an airfield of known strength. But this current engineering method does not sufficiently meet the demands in the conceptual design phase of modern aircraft capable of operating on substandard airfields and from this follows the motivation to investigate this specific problem with the software tool of MBS dynamics.

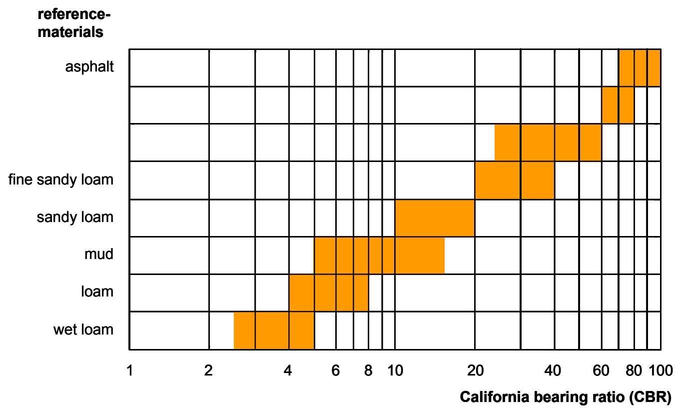

Figure 4: CBR values for different soils

Characteristic for aircraft operation on substandard airfields is the velocity dependency of rolling drag and sinkage which is quite different from that on rigid pavements [4][17][21]. In Figure 7 the velocity dependency for a rigid and soft soil surface is compared. Newly made model approaches consider the velocity dependency of rolling drag and sinkage in soft soil, but so far high speeds are not included [9]. The model approach described in this paper considers the velocity dependency of tyre-soil interaction at high speeds up to about 50 m/s. Higher velocities are not regarded because the take-off velocity of military transport aircraft can be assumed to be of that magnitude and in addition, measured data for this velocity range is available. Another common situation is the repeated loading and unloading of soil which occurs on multi-axle vehicles (the so called multipass) [11][27]. In Figure 9 the graph of the pressure gradient of a repetitive loading and unloading experiment is shown.

2.1 Rolling Resistance/ Tyre Sinkage

Analytical simulation models are based upon the methods of Bekker where the tyre-sinkage behaviour is gained from static penetration tests [2]. The basic equation of pressure-sinkage relationship is given below:

$$p = \left(k_c / B + k_\varphi\right) z^n \tag{1}$$

Therein is z the tyre sinkage, k_c the cohesion module, k_φ the friction module of soil and n the sinkage exponent. The characteristics for different soils are shown in Figure 5. Especially a wet sandy loam (sandy loam 26% moisture content) shows already for minor sinkages a yielding characteristic so that pressure doesn't increase much over sinkage. That makes these soils very critical for passing with wheeled vehicles.

A disadvantage of Bekker's equation (1) is that the parameters have variable dimensions depending on the value of the exponent n. Hence Reece proposed a new equation for the pressure-sinkage relationship [23]:

$$p = \left(ck'_c + \gamma_s B k'_\varphi\right)\left(\frac{z}{B}\right)^n \tag{2}$$

Additionally to Bekker's equation the weight density of the terrain γ_s has been introduced.

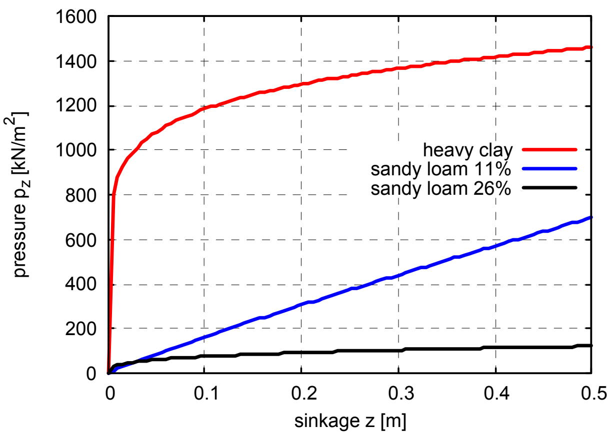

Figure 5: Pressure-sinkage relationship from Bekker

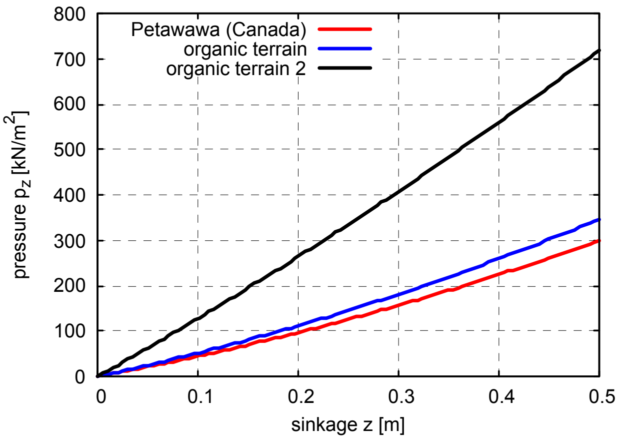

Figure 6: Pressure-sinkage relationship up to critical sinkage from Wong

Referring to Wong, equations (1) and (2) are not valid for layered soils like 'muskeg', a North American peat like soil. Therefore Wong introduced the following equation for layered organic soils [27]:

$$p = k_p z + 4 m_m z^2 / D_h \tag{3}$$

Therein is z the sinkage, k_p a stiffness parameter for the peat, m_m is a strength parameter for the surface mat and D_h is the hydraulic diameter of the contact area, which is equal to $4\,A/L$, where A and L are the area and the perimeter of the contact patch. Figure 6 depicts the pressure-sinkage relationship for different organics soils. This pressure-sinkage relationship is valid up to the critical sinkage when the surface mat collapses. From this point on sinkage would increase further more and pressure would drop towards zero and as a result the vehicle gets stuck.

2.2 Velocity dependency of rolling drag and sinkage on soft soil

The first approach for rolling drag F_{rd} and tyre sinkage z_0 with velocity dependency can be made as follows:

$$z_0 = \left[\frac{F_z}{B\sqrt{D_0}\left[N_1 + N_2 N_3\right]} \right]^{\frac{2}{2n+1}} \tag{4}$$

$$N_1 = k_{stat}\left[1 - \frac{n}{3}\right] \tag{5}$$

$$N_2 = k_{dyn}\left[\frac{2v_x}{1 - S_x}\right] \tag{6}$$

$$N_3 = \left[\frac{1}{1+m} - \frac{n}{3+m}\right]\left[\frac{z_0}{D_0}\right] \tag{7}$$

$$F_{rd} = B\left[\frac{k_{stat}}{n+1} + N_2 N_4\right] z_0^{n+1} \tag{8}$$

$$N_4 = 2\left[\frac{1}{2+m} - \frac{n}{4+m}\right]\left[\frac{z_0}{D_0}\right]^{m/2} \tag{9}$$

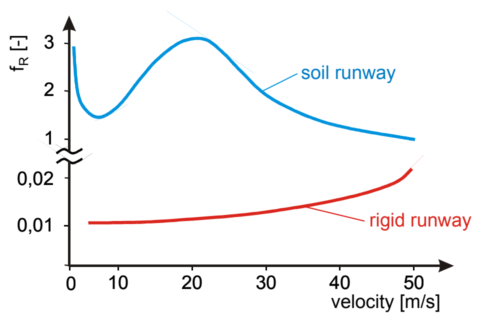

Figure 7: Velocity dependency of rolling drag on a soft and rigid surface

Most simulations and measurements that deal with tyre-soil interaction do not consider the velocity dependency of rolling drag and tyre sinkage because in most cases only low velocities are reached. This applies mainly to agricultural but also to military vehicles. Therefore mainly velocities of up to 20 m/s are taken into account. But for the operation of aircraft on soft soil runways up to 50 m/s are necessary for take-off and hence must be beared in mind for simulations and measurements. Figure 6 shows the comparison of rolling drag on rigid and soft road surfaces. In former investigations measurements have been made that regarded these high speed effects [5][22][25].

2.3 Multipass

The multipass-effect occurs when a multi-axle vehicle rolls over soft soil and the aft rolling tyres roll over a pre-compressed terrain. Important values are the tyre sinkage z_{ei} and the rut depth z_{si} (Figure 8). The tyre sinkage z_{ei} is defined as the depth of the tyre contact patch to the undeformed terrain and the rut depth z_{si} is defined as the depth of the soil after the tyre has passed and the elastic deformed part has reversed. An approach to simulate both the elastic and plastic behaviour of soil is a rheological soil model (shown in Figure 13). Here a module of stiffness μ_v and viscosity is coupled with a module of plastic yielding μ_p.

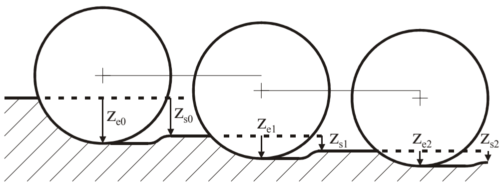

Figure 8: Tyre sinkage and rut depth with multi-axle vehicles

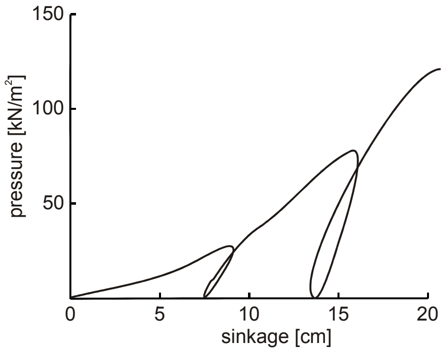

Figure 9: Repetitive loading and unloading

The simulation shown in this paper concentrates on the multipass of aircraft on soft terrain and the implementation of a tyre-soil module into the MBS software tool SIMPACK.

2.4 Finite Element Description of Soil

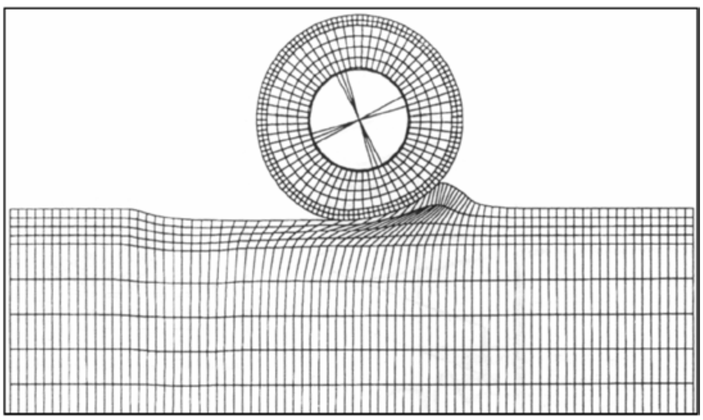

Figure 10: Two-dimensional modelling of tyre-soil interaction by Aubel [1] with bulldozing-effect

First investigations of tyre-soil interaction models by means of FE formulations were made by Aubel [1] with further studies made by Fervers [8]. Similar approaches were use by Shoop for tyre-terrain interaction on snow surfaces [26]. An example for the possibilities of two-dimensional modelling is shown in Figure 10 which also demonstrates the bulldozing effect as a bow wave in front of the wheel. As mentioned in chapter 1.2 the Drucker-Prager material law is commonly used for finite element formulations in terramechanics.

3.0 MODELLING

Figure 11 depicts the topology of the MBS model of an multi-axle landing gear. The corresponding SIMPACK model is shown in Figure 12. In the current model a rheological soil model for the elasto-plastic soil effects and a rigid tyre model are implemented. As shown below further improvement could be achieved by an analytical approximation of the tyre deformation on soft soil.

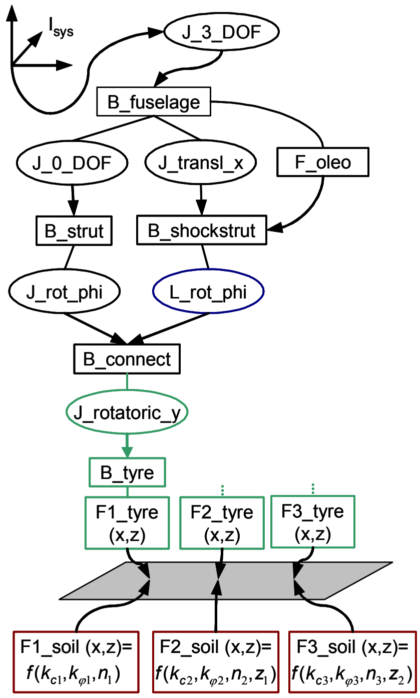

Figure 11: Topology of the MBS model

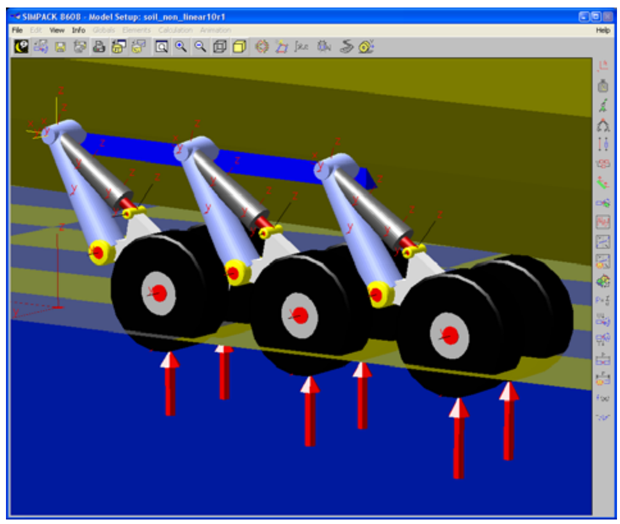

Figure 12: SIMPACK multi-axle model with soil forces depicted as arrows

3.1 Rheological soil model/ Multipass Modelling

Investigations of Bolling lead to an rheological soil model with elasto-plastic behaviour [3]. The elastic behaviour of the soil is especially important for multipass manoeuvres because it affects the soil conditions for the aft rolling wheels. The diagram shown in Figure 13 depicts the mechanical system with the elastic (stiffness c_f and Newtonian viscosity η) and plastic (compression μ_v and yielding constant μ_p) part which additionally takes into account the sinkage velocity $\dot{z}$. Below the corresponding equations are given (equations (10)-(12)).

$$p_r = c_f(z_{r1} - z_{r2}) + \eta(\dot{z}_{r1} - \dot{z}_{r1}) \qquad (10)$$

$$p_r = \mu_v z_{r2} + \mu_p \tag{11}$$

$$\dot{p}_r + \frac{c_f + \mu_v}{\eta} p_r = \mu_v \dot{z}_{r1} + \frac{c_f \mu_v}{\eta} z_{r1} + \frac{c_f \mu_p}{\eta} \tag{12}$$

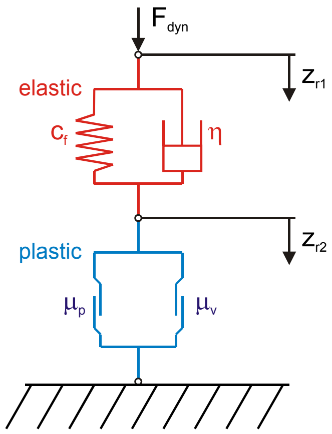

Figure 13: Rheological soil model

3.2 Tyre Modelling

In the field of terramechanics the assumption of a rigid wheel is quite a good approximation of the real contact mechanics because the tyre deflection is very small compared to its sinkage into the terrain. But nevertheless simulation quality can be improved with analytical approximations of tyre terrain contact. There are several approaches for analytical description of the deflected tyre deformation. In Figure 14 an example of approximation with a larger tyre diameter is given [12].

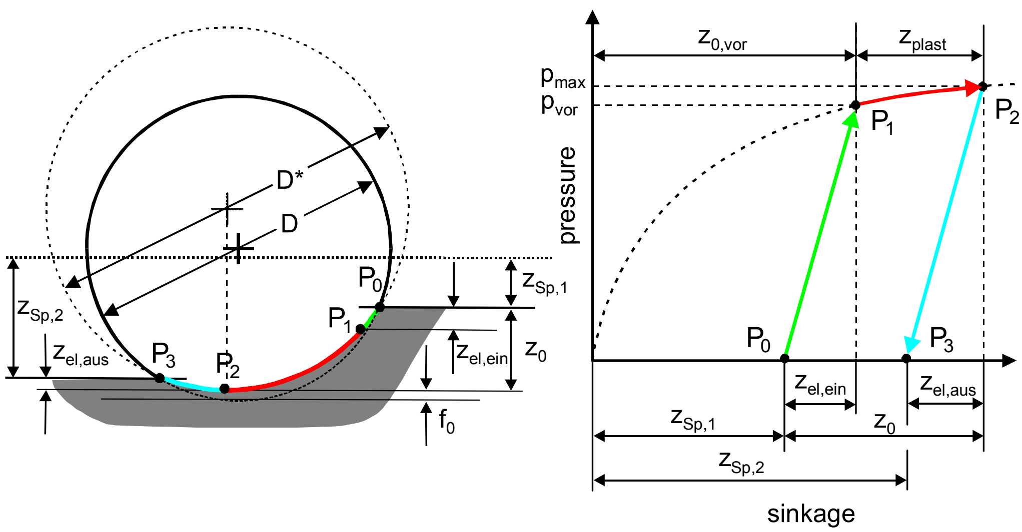

Figure 14: Substitute sphere for the description of the interaction between a pneumatic elastic tyre and the elastic soil behaviour [12]

4.0 SIMULATION RESULTS (EXAMPLES)

The simulation results presented here are calculated by means of the MBS tool SIMPACK. The tyre-soil interaction module with the elastic-plastic soil behaviour is implemented within user routines. The simulation results in Figure 15 show the crossing of a multi-axle landing gear from a rigid airfield onto a soft soil surface. This scenario can occur in an emergency case when an aircraft gets of the rigid airfield and has to roll out on an un- or semi-prepared airfield. The results show the expected characteristics so that the sinkage increases with each aft rolling tyre but the additional sinkage for each tyre decreases. That means that the aft rolling tyres roll over pre-compressed terrain.

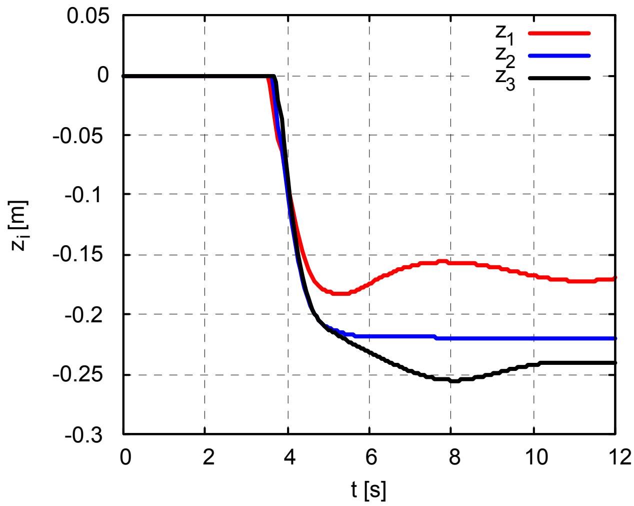

Figure 15: Sinkages for the in series rolling tyres for a multi-axle vehicle when passing from rigid road onto soft soil

5.0 CONCLUSION AND OUTLOOK

In this paper different methods for dynamic tyre-soil interaction simulation are presented. By means of MBS tools an analytical method is introduced. With the method of finite elements a numerical description of the tyre-soil contact is achieved which allows to consider the elasto-plastic soil behaviour and important mechanisms in soil deformation like soil compaction, soil movement and the bulldozing effect. The aim of the investigations is the development of a CAE tool that supports the integrated conceptual design process of multi-axle landing gears in consideration of the dynamic behaviour of the soil in interaction with the vehicle.

The MBS simulation of the rolling of a multi-axle landing gear considers the different rolling drags and sinkages of the in series rolling tyres. The additional sinkage of the aft rolling wheels is lower compared to the fore rolling wheels due to the pre-compression and therefore the multipass-effect has an influence on airfield damage. The dynamic soil behaviour is implemented into a MBS simulation environment by means of specific measurable soil parameters.

Important to mention is that the accuracy of tyre-soil simulations can not be that high because physical properties of natural soil are extremely non-deterministic. Especially the moisture content of the soil gives this medium an extremely non-linear behaviour.

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Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

P8 A. Gibbesch 'High-Speed Tyre Soil Interaction of Aircraft on Soft Runways' (DLR, DE)

After having reminded the advantages and drawbacks of the MBS (Multi-body System) simulation tools and of the FE (Finite Element) Method , this last one allowing to consider plastic and elastic deformations, the author focused on the velocity dependency of tyre-soil interaction at speeds up to about 50m/s and described simulation results calculated by eans of the MBS tool SIMPACK: he finally drew our attention on the fact that the developed CAE tool he proposes neglects some unpredictable non linear characteristics of the contact tyre-soil.

Discussor's name: C. Petiau
Q. I see in your presentation a friction factor of 3. How do You equilibrate the pitch effects on the Aircraft?
R. The measured data of the rolling resistance factor does not mean that this kind of terrain is passable by an aircraft: it just shows that the velocity dependency is considered in the simulation. The pitch effect and the possibility that the aircraft jets stuck due to the high rolling resistance is not investigated in the shown simulation results. But the presented multibody model is capable to integrate such simulation scenarios