STINA

*S*OIL *T*IRE *IN*TERFACE TO *A*DAMS

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INTRODUCTION

Measurements of vehicle vibrations are usually difficult to investigate. Very often the particular influence of different components on the vibration system cannot be separated. In such cases the systems cannot be properly explored. However, an appropriate way of investigating the phenomena is provided by simulation programs. Rigid body simulation programs (e.g. *ADAMS*) are particularly useful tools in the development of static and dynamic forces of mechanical systems.

The accessory tire module *TINA* (*Tire In*terface to *A*DAMS) enables vehicle motion to be simulated on flat and uneven ground in *ADAMS*. Curves can also be reproduced. The interaction between tire and solid road can be simulated, but the *TINA*-module is not able to investigate vehicle motion on soft ground.

At the Institute of Automotive Engineering at the University of the Federal Armed Forces Hamburg an interface to *TINA* was used to develop the new tire module ***STINA*** (*S*oil *T*ire ***In***terface to *A*DAMS). With this new module the interaction between tire and soft ground can be simulated. This paper gives some information about the structure of ***STINA*** and its implementation into *ADAMS*. Several simulation results gained with ***STINA*** are presented and discussed.

THE TIRE MODULE *TINA*

The tire module *TINA* (*Tire Interface* to ADAMS) allows the user to consider roadways with different surfaces in *ADAMS*. However, the roadways are always rigid. In addition to this *TINA* offers various mechanical models to describe the tire behaviour. With these models it is possible to determine the forces and torques acting between the tire and the ground which are involved in traction and lateral guidance as well as the oscillation behaviour. *TINA* works as a subroutine to *ADAMS*. The interaction between *ADAMS* and *TINA* is shown in **Fig. 1**.

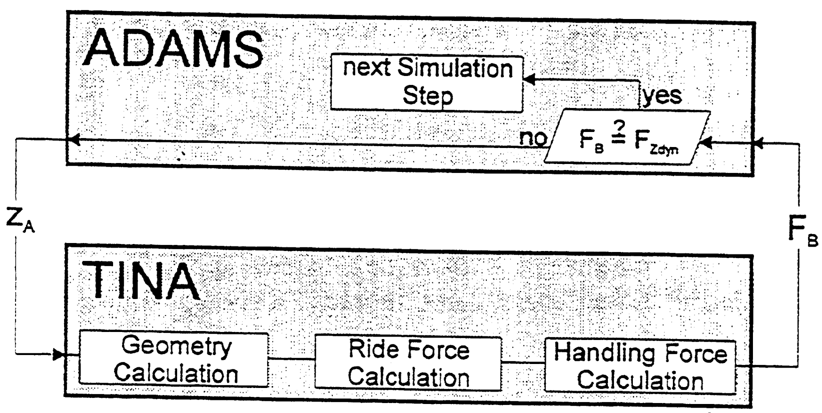

Fig. 1: Structure of *TINA* and its interaction with *ADAMS*

During the simulation *ADAMS* first calculates the subsidence z_A, related to the stationary roadway, and puts it into *TINA*. From this, the force of ground reaction F_B is determined by a chosen tire model and returned to *ADAMS*. This force is compared with the dynamic wheel force F_{zdyn}. If they are equal in tolerance, the computation of this simulation step is finished. The system then calculates the ratios for the next wheel. However, if the forces are not equal, *ADAMS* will calculate the interaction between the wheel and the ground by iteration until a solution is found. If the system does not converge after a defined number of iteration steps, the simulation will be continued with a new size of step width.

In *TINA* there are three steps to calculate the interactions:

-'*Geometry Calculation*' to calculate the geometric tire data
-'*Ride Force Calculation*' to calculate the stroke and damping of tire
-'*Handling Force Calculation*' to calculate the lateral and vertical tire forces.

The *Geometry Calculation* contains five different methods to describe the tire conditions while driving on either flat or uneven rigid roadways. For the *Ride Force Calculation* there are three methods available, which consider the differences between linear and non-linear spring and damper characteristics. The *Handling Force* can also be calculated with three different models, which consider characteristic values of rolling resistance and friction coefficient as well as lateral and camber stiffness.

THE NEW TIRE MODULE *STINA*

In order to solve the special formulation of the question: *"simulation of vehicle motion on soft ground"*, *TINA* was enlarged to ***STINA*** (*S*oil ***Tire In***terface to ADAMS).

As can be seen in **Fig. 2**, *TINA* consists of five separate subroutines. This subroutines are responsible for the initiation of fundamental data and for the calculation of *Geometry, Ride Force* and *Handling Force*. These subroutines are unchangeable. However, the structure of *TINA* allows the user to interlace his own subroutines parallel to the existing subroutines. This possibility formed the basis for the development of *STINA* [4].

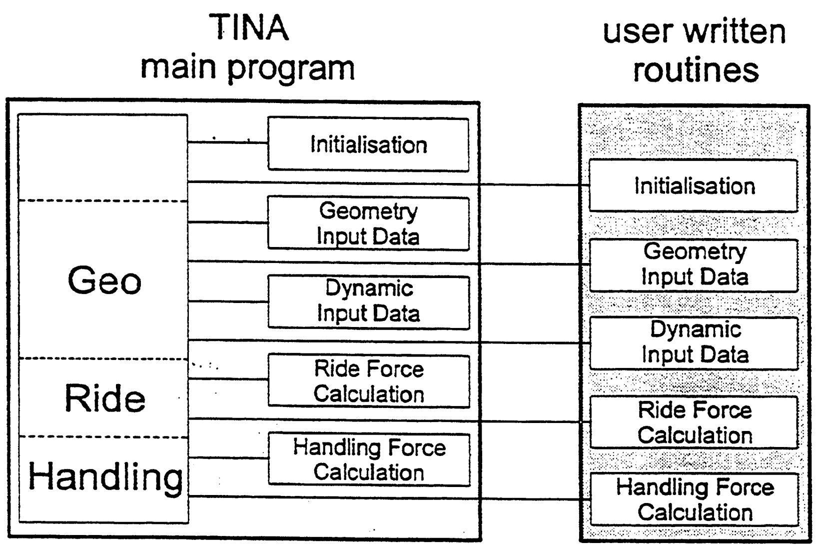

Fig. 2: Program structure of the *TINA* Software

Since the question of vertical dynamics should be discussed first, the *Ride Force Calculation* had to be changed by a *New Ride Force Calculation*. The structure of the other subroutines remains unchanged, merely the input parameters, for instance the rolling resistance coefficient, have to be adapted to the conditions on soft ground. The resulting structure and the interfaces to *ADAMS* are shown in **Fig. 3**.

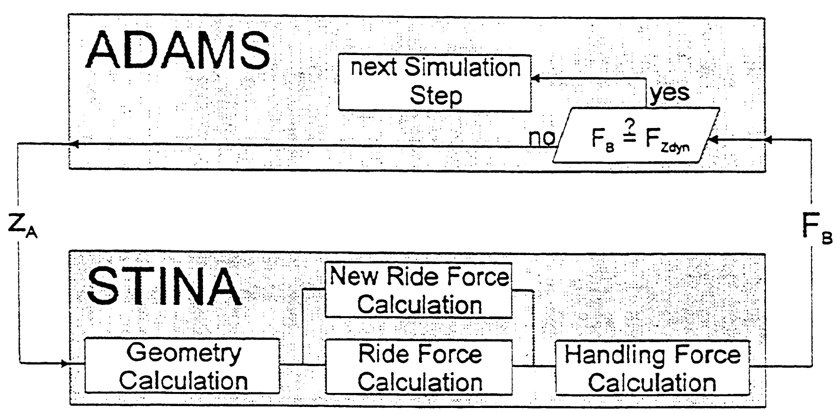

Fig. 3: Structure of *STINA* and its interaction with *ADAMS*

In order to compute the *New Ride Force*, an interaction model is needed for the calculation of the ground reaction force F_B, based on a given subsidence z_A. The current version of ***STINA*** offers two different ways: the utilisation of analytical models which describe the phenomena by means of a system of formulae, and the utilisation of results of FEM-models, which are represented by a family of characteristics (**Fig.** 4).

The contact area, which on soft ground is distinctly more complex than on solid ground, is crucial for the investigation of these phenomena.

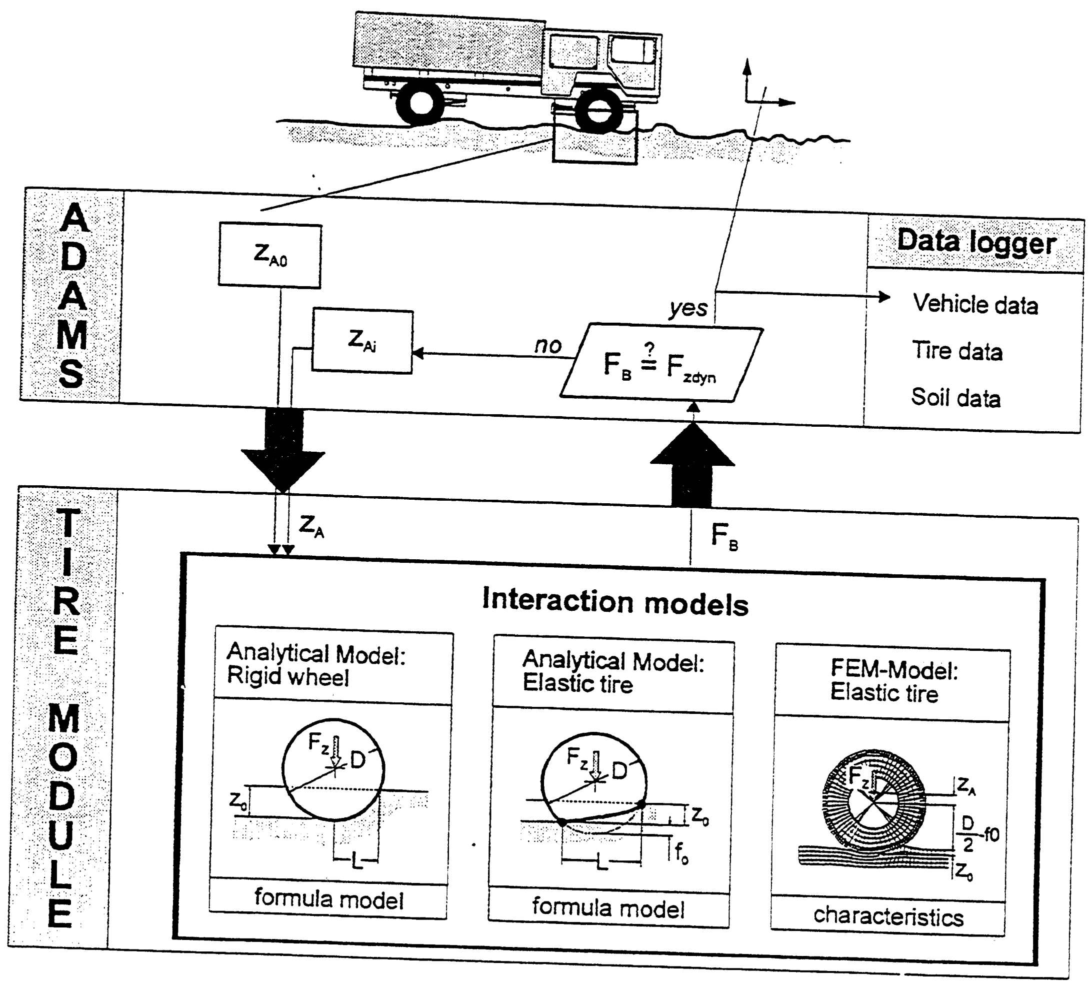

Fig. 4: Software structure of the new Tire Module ***STINA***

In the analytical approach it is assumed that the contact area cannot vary. The length of the contact area is obtained from the equilibrium of forces while taking into account the tire deflection and sinkage into the soil. The resistance of soil deformation is considered as well as the wheel load. In the current version of ***STINA*** two alternative analytical models are implemented: the rigid wheel and the elastic tire.

The analytical model of the rigid wheel

The easier of the two is the rigid wheel approach. As shown in **Fig. 5**, this describes the penetration contour of a rigid wheel on soft soil. The contact curve between wheel and soil is described as a circular arc with the wheel diameter *D*. The model is based on the well-known approach of BEKKER [5,6]. The connection between wheel load F_z and sinkage z_0 is:

$$F_Z \approx b \cdot k \cdot \sqrt{D} \cdot \left(1-\tfrac{n}{3}\right) \cdot z_0^{\,n+0.5} \qquad (1)$$

In this case, the sinkage z_0 is equal to the subsidence z_A and the wheel load F_z is equal to the ground reaction force F_B.

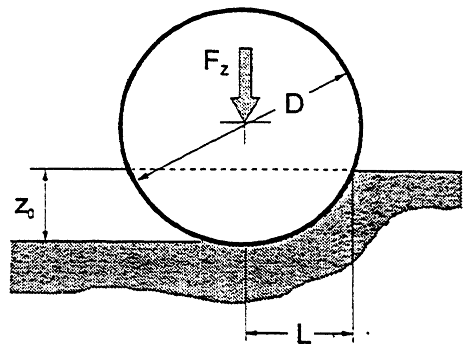

Fig. 5: Contact contour between rigid wheel and soft soil

The analytical model of the elastic tire

A more precise description of the relationship is supplied by the description of the elastic tire. The contact curve between tire (diameter *D*) and soil is described as a larger rigid wheel with diameter *D**. As the mathematical description of the contact curve in cartesian coordinates is extremely difficult, a parabolic contact line based on the rigid wheel with circle geometry is chosen [7,8].

The parabolic geometry is a good approximation to the circle with the advantage of an easy mathematical treatment. The geometry is shown in **Fig. 6**.

The initially unknown tire deflection f_0 on soft ground is derived from the tire deflection on solid ground, measured on a loading test stand as a function of wheel load F_z and the inflation pressure p_i. The connection between wheel load F_z and sinkage z_0 is calculated as follows :

$$F_Z \approx b \cdot k \cdot z_0^{n+0.5} \cdot \frac{\sqrt{1+\frac{f_0}{z_0}} + \sqrt{\frac{f_0}{z_0}}}{1+\frac{n}{2}} \qquad (2)$$

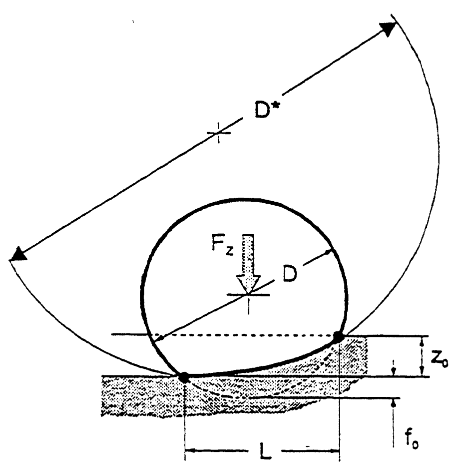

Fig. 6: Contact contour between tire and soft soil of an elastic tire

The relation of tire deflection f_0 and sinkage z_0 has to be calculated by iteration. Considering that the sum of tire deflection f_0 and sinkage z_0 is equal to the subsidence z_A, the tire deflection on soft ground can be assumed to be

$$f_0 \approx 2 \cdot \sqrt{\frac{f_0}{z_0}} \cdot \sqrt{\frac{D^*}{D} - 1} \cdot f_k \cdot \frac{D}{D^*} \tag{3}$$

The wheel diameter ratio D^*/D can be calculated as follows:

$$\sqrt{\frac{D^*}{D}} \approx \sqrt{1 + \frac{f_0}{z_0}} + \sqrt{\frac{f_0}{z_0}} \tag{4}$$

The FEM-model of the elastic tire

In addition to the analytical statements, ***STINA*** contains a simulation method that employs data gained from FEM-simulations. The data are present as a family of characteristics for different soil strength-properties and inflation pressures. The fundamental method contains an FEM-simulation of a tire-soil-interaction model with a modular structure of a tire model and a soil model (**Fig. 7**). A special feature of the model is the fact that the tire-ground interaction phenomena are the result of a realistic rolling process. This process considers the elastic characteristics of the tire deflection as a function of the inflation pressure to the same extent as the elastoplastic behaviour of soft soil as a function of density and water content [9].

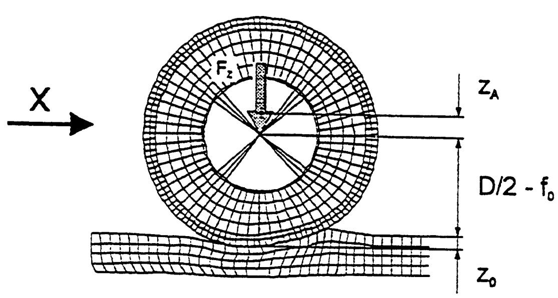

Fig. 7: FEM-simulation of tire-soil-interaction while rolling process

The correlation of wheel load F_z and subsidence z_A is an FEM-simulation result, which can be read out at each point of the rolling process, while

$$F_z = f(z_A) \tag{5}$$

The subsidence z_A is present in its components of tire deflection, f_0, and sinkage, z_0. Numerous FEM-simulations enable a family of characteristics to be established for use in ***STINA***, these characteristics are functions of wheel load, tire type, inflating pressure, soil type, soil conditions and type of wheel drive. An interpolation program within ***STINA*** ensures that ground reaction forces related to the respective subsidence values are available to cover the area between the characteristic lines.

In addition to the three models presented for the calculation of wheel-soil interaction, various soil types are also catered for in ***STINA***. Therefore the ***STINA*** module is highly flexible and can be used for investigating a large number of applications. The wheel-soil interaction models and the soil types are conducted by a library, which can be extended. This means that new models or soil types can very easily be interlaced into ***STINA*** without changing the structure.

In addition to the possibility of simulating the interactions between elastic tire and soft ground, the simulation program ***STINA*** also allows dynamic effects on soft ground to be investigated for the first time. This means the program is able to simulate vehicle vibrations indicated by unevenness on soft ground.

SIMULATION RESULTS

Several simulations with the *STINA* module were performed on the model of a wheel-mass-system. The simulated model was equipped with the tire of type 14.0R20 mil. The wheel-soil interaction model during the simulation was the model with parabolic geometry. **Fig. 8** represents the influence of different inflation pressures on sinkage z_0 and tire deflection f_0 of the wheel on soft loam.

Fig. 8a shows the conditions with an inflation pressure of $p_i = 4,5$ bar. As can be seen, the sinkage z_0 is really high in comparison to a relatively low tire deflection f_0 caused by the soft loam. **Fig. 8b** shows the conditions on loam with an inflation pressure of $p_i = 1.0$ bar. The softer tire gives a greater tire deflection, f_0, while the sinkage, z_0, becomes smaller due to enlargement of the tire-soil contact area.

This result corresponds to practical experience. The phenomena discussed are results of the static state on even ground. As can be seen in **Fig. 8**, these static states are reached after a transient oscillation. The reason for the overshoot at the beginning of the simulation is a given excitation by the user.

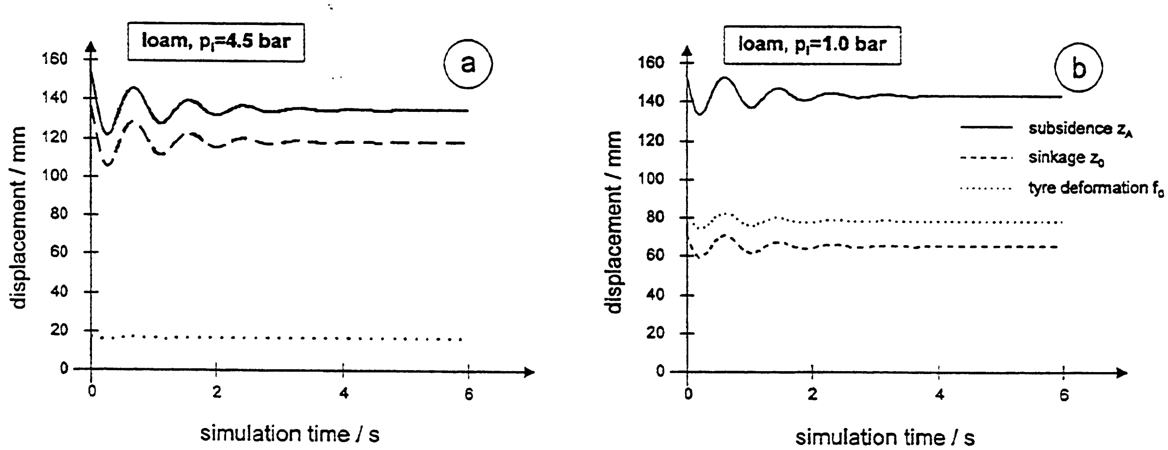

Fig. 8: Simulation result of *STINA* - vehicle drive with different inflation pressures on loam

Fig. 9 shows another simulation result for comparison. In this case two different soils are simulated: the soft loam and a firm sand. The parameters during the simulation are equal. The simulated inflation pressure was $p_i = 4,5$ bar.

As can be seen in **Fig. 9b** the tire deflection f_0 is the decisive part of the wheel subsidence on the sand. On the whole, the wheel subsidence is less than on loam and the vehicles oscillation decreases much faster than on the soft loam. These results also agree with practical knowledge.

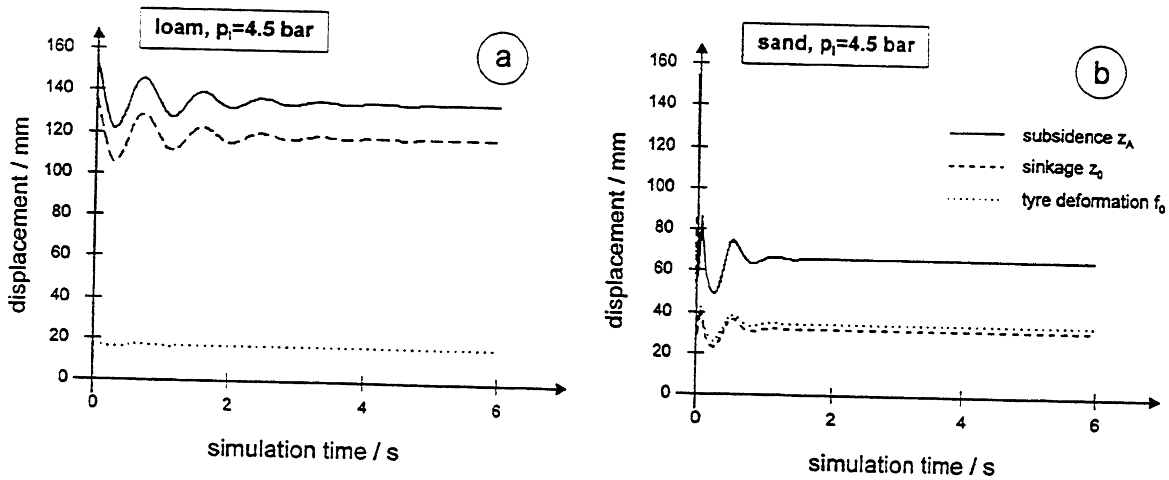

Fig. 9: Simulation results gained with ***STINA*** - subsidence, sinkage and tire deflection on even, soft ground with influence of different soil parameters; speed v = 18 km/h

The most important field of application for ***STINA*** is the simulation of vehicles dynamics in order to investigate their vibrational behaviour on soft ground. To demonstrate the influence of vehicle vibrations on soft ground, several simulations were carried out with ***STINA***. In the following some of them are presented.

The first example shows a quarter vehicle that is reproduced by a two-mass-system. The simulation results demonstrate the vibrational behaviour of the wheel and the vehicle body caused by a roadbump. **Fig. 10a** refers to the results of a simulation on solid ground and **Fig. 10b** to those on soft ground. In both cases the vehicle crosses an obstacle with a height of *0.6 m* and a length of *1.0 m*, this driving with a speed of *v=18 km/h*. As can be seen in both figures, not only on solid road but as well on soft ground the body oscillation is higher than this of the wheel. Comparing the amplitude of the body oscillation it comes into sight that the vehicles vibrations on soft ground differs significant from these on solid ground. While the vehicles vibrations, indicated on solid ground, decrease rapidly, these on soft ground takes more than three times longer to decay. This makes it obvious that the behaviour of the ground, thus the parameters of the soil take a great influence on vehicle vibrations.

Another aspect to regard is the ground-surface left behind. While the surface-contour on solid ground remains unchanged, the wheel-soil interaction on soft ground implies a modification of the surface contour. This effect has an important influence on the vibrational behaviour of following wheels. The rear wheel discovers the modified surface-contour which generate an excitation influenced by the front wheel and totally different from this on solid ground. The interference of the front wheels vibration on the rear wheels excitation and vice versa the influence of the rear wheels vibration on the dynamic load thus on the excitation of the front wheel is the most important aspect to regard with vehicle vibration on soft ground.

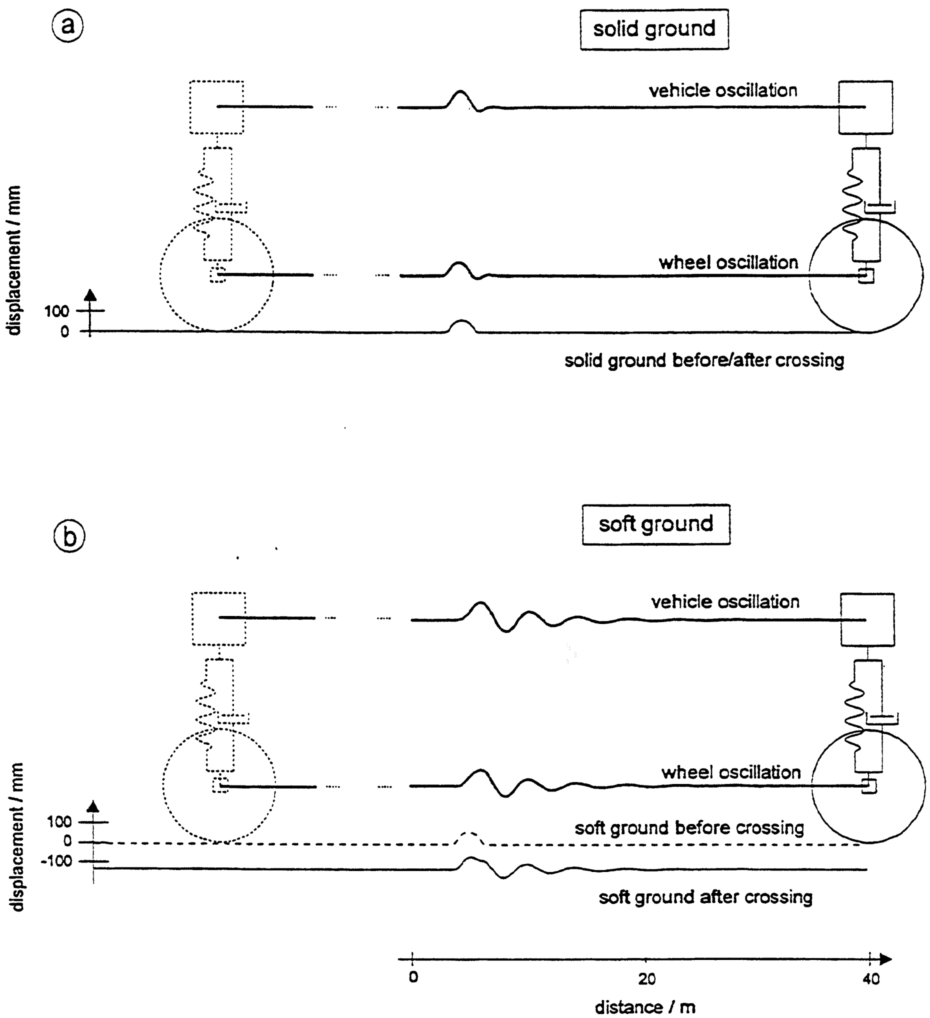

Fig 10: Simulation results of ***STINA*** - oscillation of a two-mass- system on solid (a) and on soft ground (b), v=18 km/h

To demonstrate this by an example the model of a wheeled loader was build up. The model represents the *Zettelmeyer Loader* type *ZL 3002* with a weight of 18.100 kg, a wheel base of 3550 mm and a wheel diameter of 1696 mm. This loader has an unsprung body but is equipped with an airspring supported loader used as damper weight. The *ADAMS*-model of this loader is shown in **Fig.11**.

The simulation was carried out on a soil, representing a loam of 14% water-content with an initially smooth surface. The excitation was done by dropping down the loader from a height of 100 mm. A controlled travelling speed of 18 km/h is established in this simulation. **Fig.12** shows the oscillation of the vehicles body. It is to be seen that the oscillation does not decay within a time of 10 s respectively a distance of 50 m.

Looking at the bodies oscillation on solid ground, **Fig.12**, where the oscillation decays within 6 s ($\triangleq$ 30 m) the crucial point of vehicle vibration on soft ground become even more obvious.

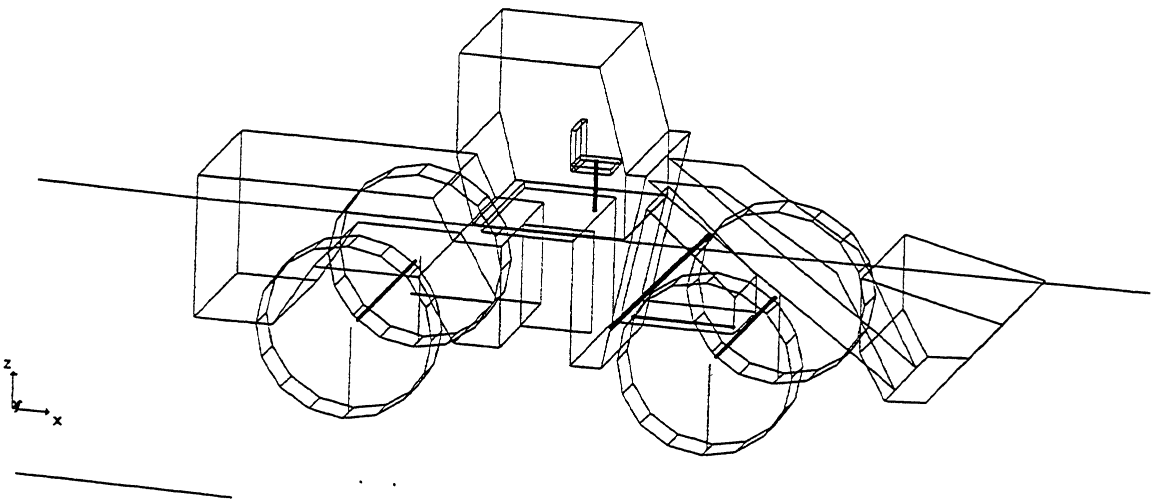

Fig 11: Equivalent of a *Zettelmeyer type ZL 3002*, modelled in *ADAMS*

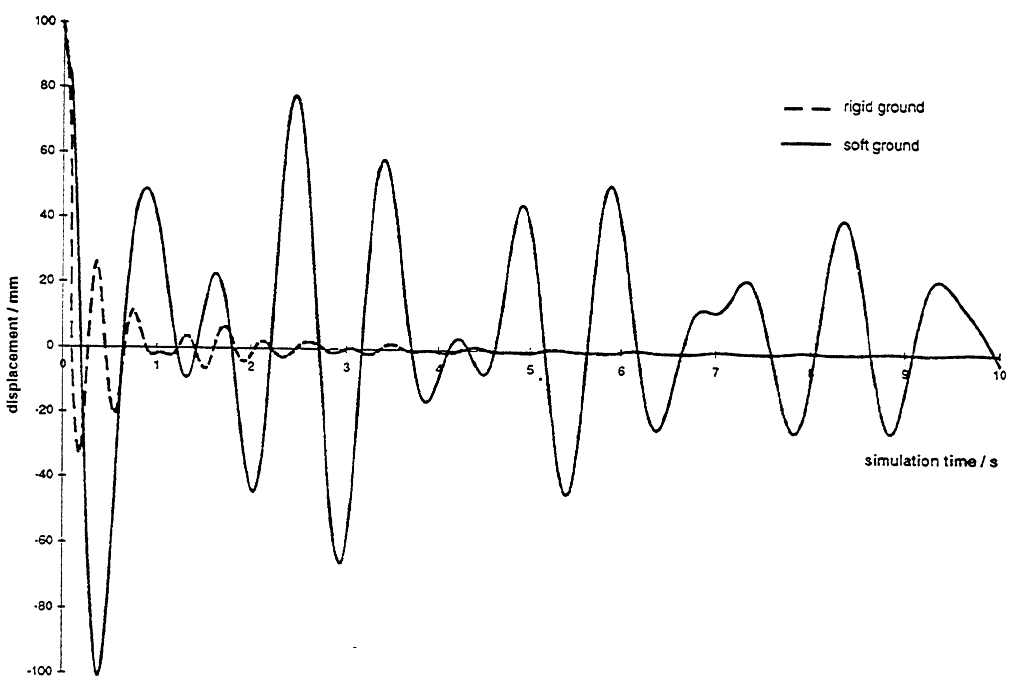

Fig 12: Simulation result of *STINA* - vehicles body oscillation on rigid and on soft ground

With respect to the conditions in field operation the riding comfort is a measure for the achievable operational speed. Here the acceleration of the drivers seat is of prior interest. As to be seen in **Fig. 13** for the simulated conditions on loam the acceleration of the drivers seat exceeds the limit of 2.5 m/s^2 even after a time of 3 seconds. After 6 sec. The acceleration reaches still values of 2.0 m/s^2. That means, that the driver of the loader is not able to drive this speed on soft ground for a longer time.

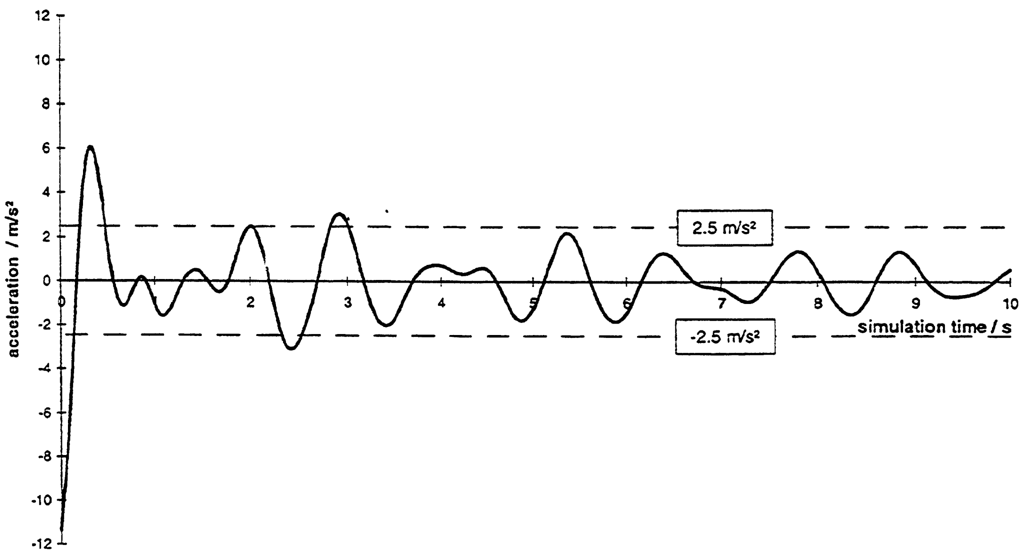

Fig 13: Simulation result of ***STINA*** - acceleration at the driver seat in vertical direction

The presented simulation results have demonstrated that the vibrational behaviour on soft ground is totally different from this on solid ground. This should be considered for the development of off-road-vehicles. To realise corresponding simulations on soft ground the module *STINA* offers a valuable extension to the simulation program *ADAMS*. Soil and vehicle data can easily be changed in *STINA* so that field trials can be reduced, which in turn means that the time and costs expended can be minimised. Up till now only the influence of vertical dynamics are implemented but for the future it is planned to consider as well the lateral and longitudinal wheel-soil dynamics.

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