Vehicle-Tyre Interface
Requirements, Concept and Design

Dipl.-Ing. K. Wolperding
Volkswagen AG

Dipl.-Ing. A. Fandre
VW-GEDAS

Prof. Dr.-Ing. Ch. Oertel
FH Anhalt

1 Introduction

ADAMS has been installed at Volkswagen AG for 9 years now. In the field of chassis development, both suspension analysis and full vehicle simulations have been employed since this time. In conjunction with the dynamic model processor DMP and a suitable user interface, ADAMS was already expanded back in 1987 to a functional tool which supports variable model development, simulation and data evaluation in a comfortable, reliable manner [7] The system MOGESSA is capable of assembling working parts or complete vehicle models from a database containing the current design states. On the ADAMS side, simulation technology was constantly perfected with new methods, e.g. in the simulation of control or in the area of flexible body behaviour.
In the recent past particular advances have been made in the description of tyre characteristics [1], so that today tyre models ranging from simple models for steady state conditions on a plane road to complex models for simulating the tyre's own dynamics when crossing obstacles are available. The desire arose to retain the already high level of efficiency, comfort and safety in the link-up to ADAMS. In the following, first the specifications are described and then the derived concept and the technical implementation discussed.

2 Characteristics of the Simulation Environment for Vehicle Tyres from the User's Standpoint

The applications of ADAMS models range from more or less stationary axle kinematics (Fig. 1) to the horizontal dynamics (Fig. 2) to the field of comfort research (Fig. 3). This results in the desire for a range of tyre models which provides tailor-made models adapted to the study purposes. Here a wide selection ranging from empirical zero-order models [6] to physical models of the zero to third order [2] to models of the nth order [4] are available today. It is currently not possible to link these models to ADAMS with a uniform, closed method. However, in this case a flexible interface is practical, both in order to allow the analysis engineer to concentrate on physical modelling, and to be able to introduce new developments in the description of tyre characteristics to ADAMS.

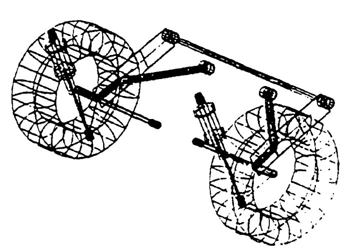

Figure 1: axle model

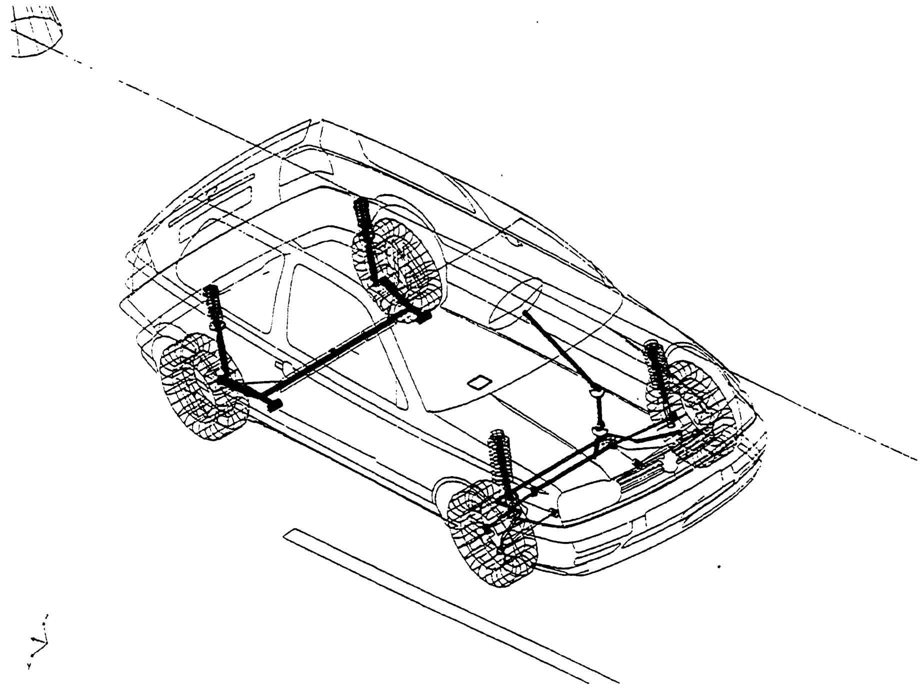

Figure 2: Full vehicle model on plane road

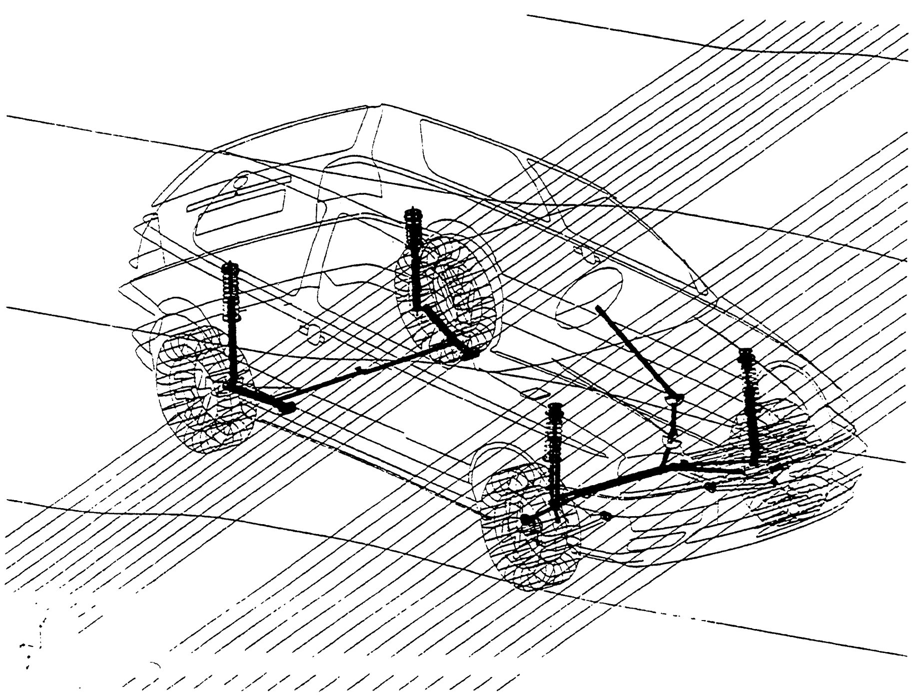

Figure 3: Full vehicle model crossing an obstacle

Several of the main aspects involved are explained in greater detail in the following.

Distribution of the wheel as an element:

The rim should be still a part of the MKS model, to base the input and output variables of the interface on its centre. This already contains the required kinematic state variables. In addition, the drive and braking torques remain part of the ADAMS simulation with its diverse possibilities. In particular, it is possible to eliminate the simulation of the centre of tyre contact on the ADAMS level. Another advantage lies in the fact that no variables, such as the direction of roll or slip, need to be defined on the ADAMS level. If necessary, these are generated shortly before calling up the tyre model.

Variability:

It is to be possible to link tyre models with different approaches to the vehicle model in a uniform manner for the user. The interface is also to be able to integrate possible new developments, and must therefore be openly structured.

Mechanical functionality:

In addition to the handling of the various transformations between the rim, tyre and contact patch, the following requirements also exist:

- Expandability of steady-state tyre models with the transient behaviour.
- The taking into account of special cases, such as static equilibrium or lifted wheel.
- Starting off with stopped wheel and braking to a stop.
- Modules for vertical load and estimation of rolling resistance.

Here the tyre model must also be provided with supportive measures if necessary. With regard to the terrain option, an access comfortable for the user must be selected. Instead of having to mesh the entire roadway including its normal vector, the user is to be able to access a library of different pre-fabricated terrain structures and edit a road from it.

Numerical functionality:

A main requirement is a high numerical stability which also covers tyre models requiring a controllable integration process for the step sizes. These kinds of simulations are to be linked with optimal calculation time and sufficient accuracy. Guidelines for the parameters of the most suitable ADAMS solver (error limit, minimum or maximum step size, permissible number of corrector iterations) are required as well as defaults.

Structural decoupling:

Only vehicle-related data and data of the numeric control are transferred on the ADAMS level. This reduces the number or transfer parameters to a clear minimum. Parameters for the tyre model and terrain option are not declared in the ADAMS data record, but instead via external files. This functional separation simplifies data management when preparing version calculations and integrating libraries for tyre parameters.

Use:

As an interface, the ADAMS user expects an ADAMS statement which produces the connection to the tyre model with simple operability and low data entry effort. Interface definitions as per [3] or [5] on the programming language level are not sufficient at this point, however are necessary on the routine level. As an interface tailor-made to ADAMS is required here, other ADAMS statements (practical: `STRING/ ,REQ/, DIFF/`) may also be used. Compatibility with ADAMS/VIEW must be ensured with regard to future products. Of course, the interface features descriptive error messages and the checking of user data for consistency. When making output data available for interpretation by the user, an integration of the ADAMS requests and the ADAMS graphics is provided.

Documentation:

For the interpretation of the results, a detailed user manual is required which describes the algorithms, axis systems and physical approaches in detail and with cross-references to the source code. In addition, operator instructions including an explanation of the error messages is also required.

3 Integration of Tyre Models in the Simulation with ADAMS

The user requirements named above must be uniformly met for a variety of tyre model classes. The division of various model types into classes is based on the following characteristics:

a) Models with algebraic equations,

b) Models with ordinary differential equations,

c) Models with partial differential equations.

Class a) includes both models with physically motivated equations and those that are purely empirically oriented. In the sense of multibody dynamics, linking elements are present here without their own state variables, and the reaction to a fluctuation of the input variables takes place without a time delay. Their application lies in the driving dynamics for stationary or low-frequency processes on a plane road. The models in b) are characterised by - generally few - linear or non-linear differential equations. In these equations the contact between the tyre and the road is not dealt with. They require no additional constraints and can therefore easily be treated with any desired integration method, for example also within ADAMS. Depending on the order of the differential equations, such models react to changes in the input variables with a corresponding transitional behaviour, and thus allow simulation in the range of low to medium-frequency input. The last class contains models which calculate the deflections in the contact area at discrete points. Models which take the structural dynamics into consideration also fall in category c). It is characterised by the fact that additional time-dependent variables, which control the constraints of friction and contact, are added to the differential equations in the model equations. In particular the constraints of contact require checking via the state variables of the model equations, and for numerical integration with multi-step processes also the modification of states variables past the actual timestep. However, ADAMS does not allow such changes, i.e. within user routines there is no possibility to modify the equation states at $t - \Delta t$ used by the multi-step method in accordance with the constraints. Although a limitation to processes with the order of one would solve the problem, the efficiency of the integration would be considerably impaired. This results in the need to permit external integration processes within class c) which must be synchronised with the ADAMS-internal process.

4 Structure of the Tyre Model Environment

From the typification given above and the user requirements, a structure results which, with regard to the connection between the vehicle and tyre models, demonstrates a separation of tasks into mechanical and numerical coupling of the tyre and vehicle model (Fig. 4).

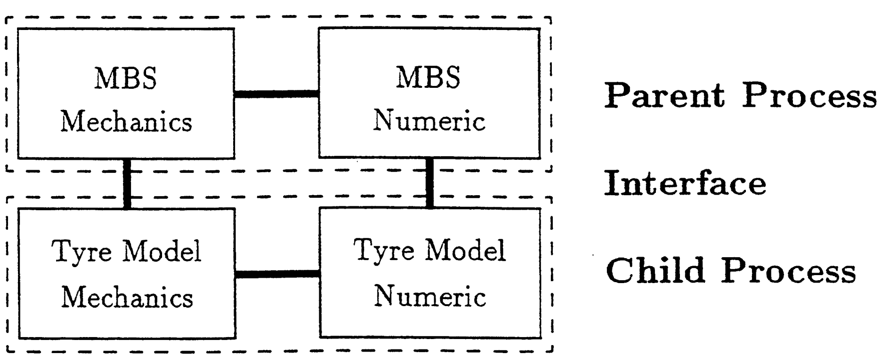

Figure 4: System and coupling

4.1 Mechanical coupling

The rim acts as a link between the tyre and the vehicle. For a known rim state (location, position, translatory and rotary velocity and acceleration), the input variables for each tyre model can be determined. The processing of the information from the rim state is model-dependent. While, for example, empirical models operate with variables such as longitudinal and lateral slip, in category c) the velocities and, if necessary, the acceleration of the rim are expected. Therefore, variables derived in a general coupling, such as specific slip definitions, are not agreed upon as general inputs. As the formulation of the above rim state is dependent on the basis, a basis system must still be agreed upon as a reference. Here the inertial basis, which is agreed upon in each vehicle model, offers itself. The forces on the rim centre and the rim torques, represented in the inertial basis, are returned accordingly. The coupling definition is supplemented with a terrain model. In it z coordinates of the road surface are specified as a function of the location $z(x,y)$. In the simplest case, the terrain is represented as a plane surface parallel to the surface spread out by $\vec{e}_1$ and $\vec{e}_2$ of the inertial basis, however the terrain model also permits the modelling of a test stretch with parametric obstacles or profiles in the form of discrete values $z_i(x_i, y_i)$.

4.2 Numerical coupling

The structuring of the numerical coupling between the processes *vehicle model* (parent process with the state vector $\underline{q}_P$) and *tyre model* (child process with the state vector $\underline{q}_C$) is highly dependent on the integration process used for the calculation of the vehicle equations. While explicit integration methods do not require the specification of the Jacobi matrix of the system, this is required for implicit one's. The equations of the total system

$$\underline{f}_P(\dot{\underline{q}}_P, \underline{q}_P, t) = \underline{r}_{PC}(\underline{q}_C, \underline{q}_P, t) \tag{1}$$

$$\underline{g}_P(\underline{q}_P, t) = \underline{0} \tag{2}$$

$$\underline{f}_C(\dot{\underline{q}}_C, \underline{q}_C, \underline{q}_P, t) = \underline{0} \tag{3}$$

are coupled via the input and output variables. Here the variables

$$\underline{J}_C = \frac{\partial \underline{r}_{PC}(\underline{q}_C, \underline{q}_P)}{\partial \underline{q}_P, \bar{t}} \tag{4}$$

in the Jacobi matrix of the parent process must be calculated, and the analysis of (4) generally takes place numerically, i.e. with a differential quotient. Under certain conditions this may involve considerable effort, which is dependent on the model equations of the tyre model and results from the evaluation of the right-hand side of (1). In addition, in category c) the elements of (4) itself can only be determined through the integration of time. If the specification of the dependencies in accordance with (4) are now eliminated in favour of the calculation time, a less accurate step size estimation results, which may lead to step repetition in certain cases, however the total calculation time is reduced due to the eliminated evaluations as a result of (4). The calculation accuracy is not influenced by this question. For the classes a) and b) the dependency of the right-hand side of the equation system can always be indicated. Another aspect of numerical coupling concerns the synchronisation of the integrations for models of the category c). The condition for this is the determinability of the state which the parent process is in when the child process is called. For processes with step size control, a distinction must be made between when the parent process has accepted a step and when, for example, a corrector iteration is present or another step must be carried out with a reduced step size. The condition for this is the accessibility of the information on the last accepted point in time, from which the respective *reason* for the call can be derived in relationship to the current point in time. If this information is not available, the processes cannot be efficiently coupled.

5 Realisation

The realisation is based on the conditions of the system ADAMS. In contrast to a system-independent interface, which must fulfil all agreements in the sense of a fixed programming environment, a more conformable environment can be created in this way which uses the features offered by ADAMS and limits the changes to be made by the user for a transition from one tyre model to another purely to the level of a single file (namely that of the vehicle model). A distinction is made between the level of the user, who would like to choose between the different models in the easiest possible manner, and the routine level, which, with its modular design, allows an expansion of the model library size.

5.1 Communication with the user

A generally parameterized `GFORCE` statement is available to the user, which is equipped with the following main parameters

- Tyre model type
- Rim marker
- String ID for the path and name of the required data records and output files.

Here only the model type and the entries in the `STRING` statements of the ADAMS deck must be changed when changing the model. All other adaptations are carried out within the corresponding routine below `GFOSUB`. In order, in addition to the usual outputs, to also make specific variables of the models accessible to graphic representation, the models are provided with their own `REQSUB` routines. The user can apply the corresponding statements in the deck. Finally, the possibility of outputting data for the animated representation of the tyre structure with A-VIEW is also implemented for some type c) models. The interval at which the required data are to be made available is also described with parameters of the `GFORCE` statement.

5.2 Structure of the environment routines

The environment routines are divided into the elements

- general functions (checking of parameter consistency, communication with ADAMS for the determination of the rim state, terrain model...),
- model-type-dependent functions (synchronisation of the integration process, treatment of the Jacobi matrix structure,....),
- model-dependent functions (processing of the rim information, generalisation of the model reaction,...).

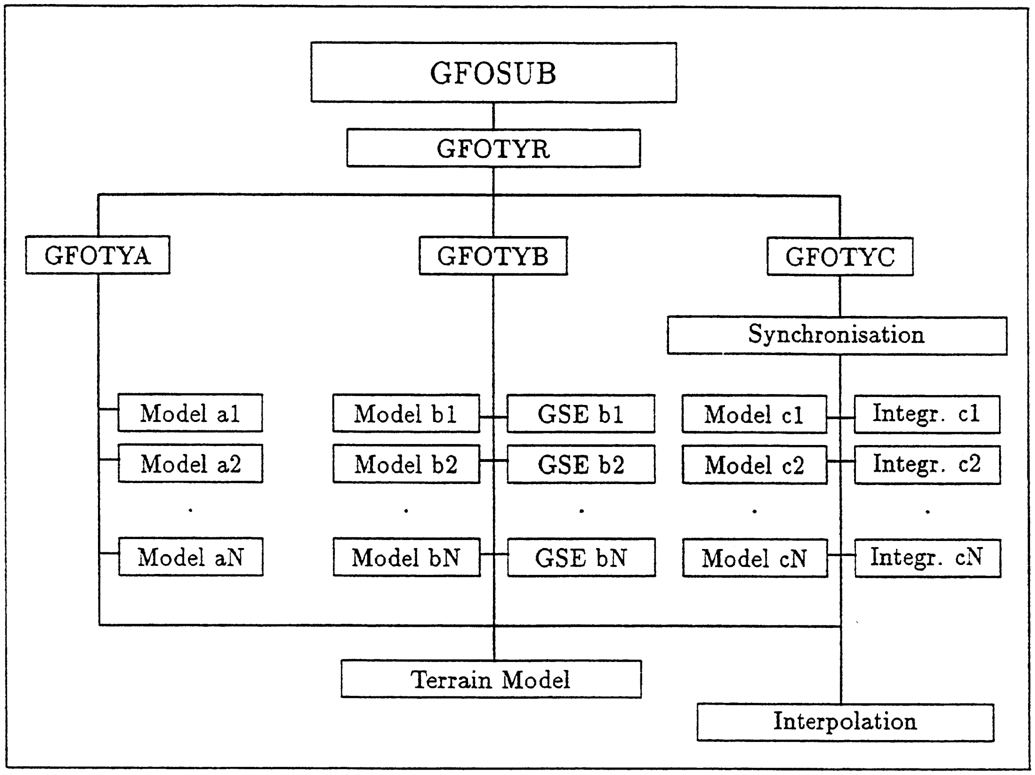

Figure 5: tyre model environment

The elements are arranged in a hierarchical structure (Fig. 5), in which the model-type-dependent general tasks are performed by the routine GFOTYR directly below GFOSUB and branched out in accordance with the type code. The routines GFOTYA to GFOTYC assume the model-type-dependent tasks. For type b) use is made of the possibility to integrate ordinary differential equations GSESUB. In addition to a synchronisation function, all models of type c) also use the possibility to calculate state variables of the parent process at intermediate points (at which no step of the ADAMS integration process are present) via the interpolation routine if the step size of the external integration is smaller than that of the ADAMS integrator.
New tyre models can easily be added to the existing environment. The categorisation allows an assignment of a new model to one of the three groups, and the definition of the coupling with the rim state specifies that the processing of these variables to model-specific inputs must be carried out in the model-related routine.

6 Results

The ADAMS interface was initially developed for the integration of physical tyre models. The linking of (numerically easier to handle) algebraic models was illustrated using the example of the "Magic Formula". Two simulations are presented as examples for the use of the interface. The first is an unsteady, horizontally dynamic driving manoeuvre with the entire vehicle from Fig. 2. The ADAMS model was automatically assembled from the MOGESSA database. It contains a (disconnectable) speed controller and a course controller, and is coupled to the "Magic Formula" tyre model [6]. From turning with a constant velocity, the vehicle is delayed through decoupling and braking. Measurements have been taken for the same driving manoeuvre which are also illustrated. The oversteer and the agreement between the measurement and the calculation can be clearly seen from the yaw rate (Fig. 6). The second example is also an driving manoeuvre, however here from the area of vertical dynamics. In order to retain the ability to make a statement with regard to the expected high-frequency vibration phenomena, the description of the mountings and suspension had to be defined more precisely compared to Example 1. A physical tyre model in accordance with [1] is connected. The vehicle drives straight ahead over two obstacles on the road at a constant velocity and Fig. 8,9 show the calculated and measured accelerations of the wheel hub in longitudinal and vertical direction. These are a measure of the comfort of a vehicle on poor stretches of road. As the results in vertical directions show only small differences between measurement and calculation, it can be seen form the results in longitudinal direction, that here some work on the estimation of the tyre-model's parameters may be necessary.

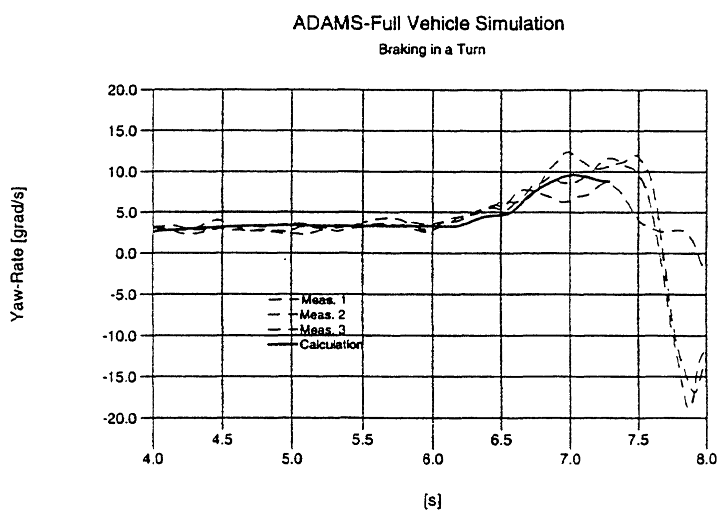

Figure 6: Yaw rate, calculated with model form Figure 2

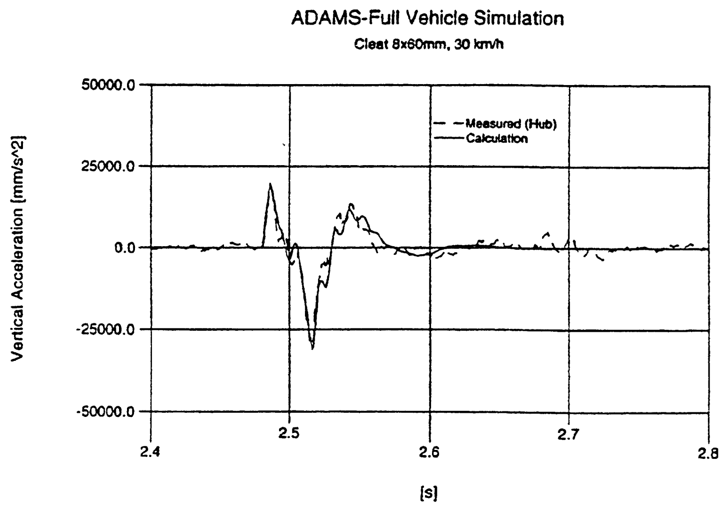

Figure 7: Calculated and measured acceleration, wheel hub in vertical direction.

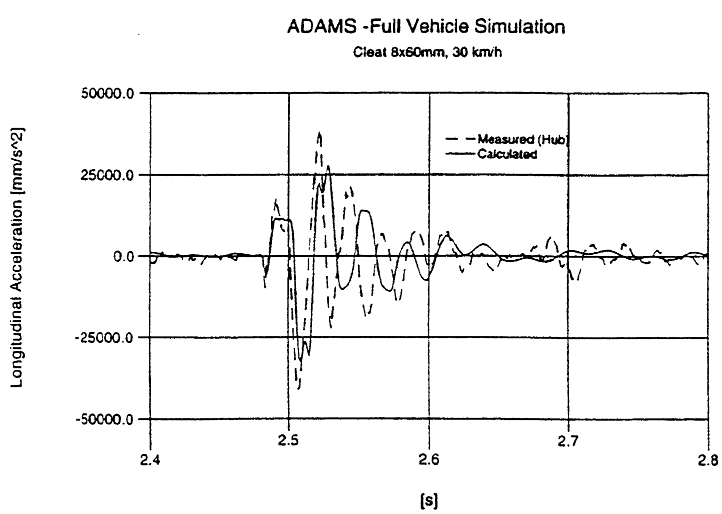

Figure 8: Calculated and measured acceleration, wheel hub in longitudinal direction.

7 Conclusion

The integration of any desired tyre models for an extremely broad range of tasks with a uniform structure presented here allows the user to select the optimal tyre model for his/her vehicle model depending on the task without having to carry out any adaptation work or changes in vehicle model or the related routines. Solely on the level of the ADAMS deck, it is sufficient to change a few parameters to be able to conduct the simulation with a different tyre model. With the definition of a uniform coupling for the mechanical variables and the numerics, all tyre model types can be integrated in the environmental structure, and in particular newly added routines can also be quickly and easily linked through clearly defined requirements for their functionality. The user comfort has been considerably increased through the provision of the interface. All tyre models currently available on the market can be tied in with high numerical reliability. In particular, it has been possible to include physical tyre models with their own degrees of freedom in the ADAMS integration process. In the process, algorithms were developed which can also lead to progress in other questions, for example in the area of driver models. The resulting productivity and functionality increases make a contribution to shortening the product development time.

References

[1] Bannwitz, P., Böhm, F., Oertel, Ch.: *Reifenmodelle und ihre experimentelle Überprüfung.* SFB 181 Abschlußkolloquim, TU Berlin 1995

[2] Böhm, F.: *Reifenmechanik, Fahrzeugdynamik, Schwingungen, experimentelle Mechanik - Berechnung von schnellveränderlichen Fahrzuständen und Energieverlusten des Automobils.* Düsseldorf, VDI-Bericht 553, 1989

[3] Eichler, M., Oertel, Ch.: *Zur Standardisierung der Schnittstelle zwischen Reifenmodell und Fahrzeugmodellen.* ATZ Automobiltechnische Zeitschrift 96(1994)

[4] Kollatz, M.: *Kinematik und Kinetik von linearen Fahrzeugmodellen mit wenigen Freiheitsgraden unter Berücksichtigung der Eigenschaften von Reifen und Achsen.* Düsseldorf, Fortschritt-Berichte, VDI-Reihe 12 Nr. 118, 1989

[5] N. N. *The TYDEX Interface.* Vehicle System Dynamics, to appear

[6] Pacejka, H. B., Bakker, E.: The Magic Formula Tyre Model. Tyre Models for Vehicle Dynamics Analysis. Proceedings of the 1st Internation Colloquium on Tyre Models for Vehicle Dynamic Analysis held in Delft, Oct. 21-22, 1991

[7] Terlinden, M., Schramm, K.: *Unterstützung integrierter Berechnungskonzepte durch wissensbasierte Interpretation in der Fahrwerksentwicklung.* VDI Bericht Nr. 816, 1990