ADAMS/FTire - A Tire Model for Ride & Durability Simulations

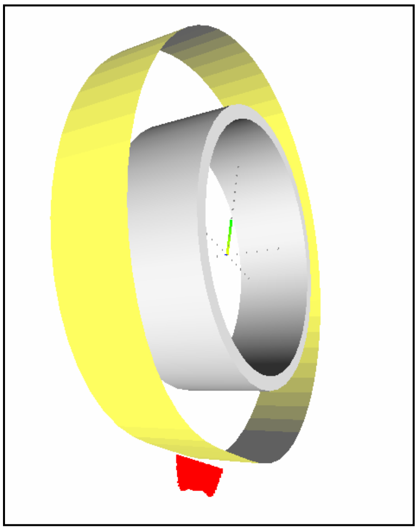
Prof. Michael Gipser
Esslingen University of Applied Sciences, Germany (www.fht-esslingen.de)
COSIN Software, Germany (www.cosin.de)

Abstract

The tire model *FTire* (**F**lexible Ring **Tire** Model) serves as a sophisticated tire force element. *FTire* is used for vehicle ride and durability investigations, or other vehicle dynamics simulations on even or uneven roadways. It is planned to make *FTire* available in ADAMS Version 11.

In the presentation, some details of the modeling approach are given, together with a discussion of the model parameters and their obtaining, some sample validation results, computing time measurements, a closer look on its program interfaces, and some planned future expansions.

A limited, stand-alone *FTire* evaluation program for Windows can be down-loaded from www.cosin.de.



1. Development Aims and Application Range of *FTire*

FTire is designed as „2½-dimensional" nonlinear vibration model. The tire belt is represented by a slim ring, that can be displaced and bent in arbitrary directions relative to the rim: vertically, longitudinally, and laterally. This approach had been chosen as a compromise between true spatial models like the authors tire model *DTire* (**D**ynamic Nonlinear Spatial **Tire** Model, cf. [4]), that tends to be very time-consuming, and pure in-plane models like the authors model *CTire* (**C**omfort **Tire** Model, cf. [7]). The latter class of models can not be used simultaneously for ride/durability **and** handling investigations without adding empiric models like Magic Formula for out-of-plane forces and moments.

The main objectives during development of *FTire* have been:

- ease of implementation, with multiple instances, into general MBS software,
- fully nonlinear,
- valid in frequency domain up to approximately 120 Hz,
- valid for obstacle wave lengths in rolling direction up to half the length of the foot print,
- observing also road transversal inclination, but not short-waved obstacles in lateral direction,
- optionally, natural frequencies and damping factors of the linearized model used as input data,
- physical model for in-plane as well as out-of-plane forces and moments,
- computational effort no more than 10 .. 20 times real time, depending on platform,
- high accuracy when passing single obstacles like cleats, pot-holes, and curb-stones,
- sufficiently accurate in prediction of steady-state tire characteristics,
- preparing model extensions to get a true downward compatible 3D model.

Apparently, these objectives were hard to meet with existing tire models. Mainly the demands on computing time vs. accuracy required a careful review and improvement of existing numerical methods.

2. Modelization

The following modeling approach has been chosen:

- the tire belt is described as an **extensible and flexible ring** carrying bending stiffnesses, elastically founded on the rim by distributed stiffnesses in radial, tangential, and lateral direction. The degrees of freedom of this ring are such that rim in-plane as well as out-of-plane motions are possible. The ring is numerically approximated by a finite number (50...100, say) of point masses. These belt elements are coupled with their direct neighbors by stiff springs and by bending stiffnesses both in-plane and out-of-plane. The radial stiffness between a single belt element and the rim is refined by a parallel connection of a spring with a spring-damper series connection to allow for dynamic stiffening of the overall tire radial stiffness at high wheel speeds;

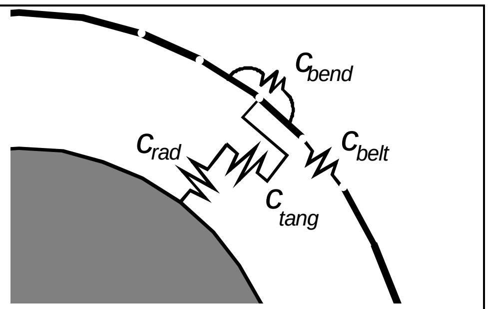


Fig. 1: Belt representation in *FTire*, in-plane part (simplified)

- all stiffnesses, bending stiffnesses, and damping factors may be calculated during pre-processing, **fitting measured static and modal tire properties**, cf. the discussion of parameters below;

- to every belt element, a number (5...10, say) of mass-less **tread blocks** is associated. These blocks carry nonlinear stiffness and damping properties in radial, tangential, and lateral direction. The radial deflections of the blocks depend on road profile, locus, and orientation of the associated belt elements. Tangential and lateral deflections are determined by the sliding velocity on the ground and the local values of the sliding coefficient. The latter depends on ground pressure and sliding velocity. „Radial“, „tangential“, and „lateral“ is to be understood relatively to the orientation of the belt element, whereas „sliding velocity“ is the block end point velocity projected onto the road profile tangent plane. By polynomial interpolation, certain precautions have been undertaken not to let the ground pressure distribution mirror the polygonal shape of the „belt chain“;

- all 6 components of tire forces and moments acting on the rim are calculated by integrating the forces in the elastic foundation of the belt.

Thus, the resulting overall tire model is accurate up to relatively high frequencies both in longitudinal and, as far as tire vibration modes are concerned, in lateral direction. There are little restrictions in the applicability with respect to longitudinal, lateral, and vertical vehicle dynamics situations. *FTire* deals with large and/or short-waved obstacles. It works out of, and up to, complete stand-still, with **no** additional computing effort **nor** any model switch. Finally, it is applicable with high accuracy in such delicate simulations as ABS breaking on extremely uneven roadways, etc.

Kernel of the *FTire* implementation is an implicit integration algorithm that calculates the dynamic belt shape. By use of this implicit integrator, the belt extensibility may be chosen to be extremely small. By this, *FTire* also allows the simulation of an in-extensible belt without any numerical drawbacks. In ADAMS™, this „local sub-system integration“ co-operates well with the original ADAMS™ integrators.

3. Implementation and Interfaces

FTire is fully implemented in ANSI Fortran 77, running on all important Unix platforms including Linux, as well as with all 32-bit Windows operating systems. In addition to the ADAMS/Tire™ implementation, a stand-alone *FTire* simulation environment for both NT and Unix/Linux is available. This environment can be used to facilitate model parameterization and validation, and to prepare full vehicle simulations with ADAMS™.

There are two different program interfaces to *FTire* available:

- a **time-discrete interface** that best fits to the internal structure of *FTire*. This interface is used in several vehicle dynamics simulation packages of major vehicle manufacturers and suppliers. The interface is such that arbitrarily many instances of the *FTire* model, with individual data, can be run simultaneously;

- the **time-continuous TYDEX/STI interface** (STI Version 1.4), cf. [6]. Initially, this interface had been defined to be used in commercial MBS-codes such as ADAMS™. Again, this interface allows for several instances to be run simultaneously.

In ADAMS™ Version 11, the preferred *FTire* time-discrete interface will be used and incorporated into the ADAMS/Tire™ interface. This is done in terms of a new internal TYRSUB subroutine, which in turn uses the TYDEX/STI calling convention. To make this approach work well, extensive numerical tests have been conducted to take full advantage of both *FTire*'s physically based use of some discrete states, and ADAMS™'s high-accuracy, step-size controlling integrators.

In either case, the coupling to the vehicle or suspension model of the calling program is done by the **rigid-body state variables** of the rim, namely

- **position** of the rim center in the global co-ordinate system,
- **translational velocity vector** of the rim center,
- **angular orientation** of the rim, defined by the transformation matrix from the rim-fixed frame to global frame,
- **angular rotation velocity vector** of the rim.

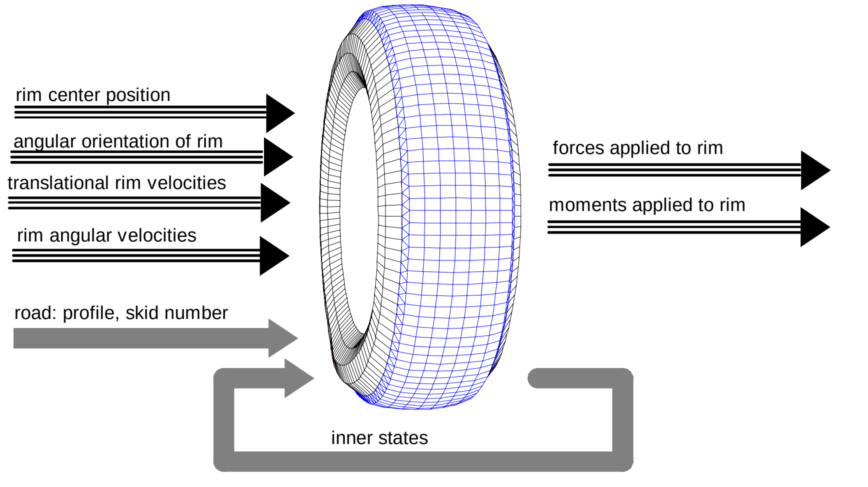


Fig. 2: Input/output behavior of the standard time-discrete interface

These values are the input to the *FTire* model. On the other hand, *FTire* provides as output

- the **tire force vector**, acting on the rim,
- the **tire moment vector**, acting on the rim.

Point of reference for forces and moments is chosen to be the rim center.

When calling *FTire* from within ADAMS™, of course there is no need to care about the meaning of these variables. They are automatically extracted from, or transferred to, the vehicle model by ADAMS/Tire™.

The **road profile** or road surface, resp., is fed into *FTire* via a very general and simple interface, for which several implementations exist. One of these implementations is the STI recommendation for road surface description used in the TYDEX interface (cf. [6]). For a user-specific road description, the only thing that is needed is a subroutine that is able to calculate the **road height** z (and optionally the road surface **skid number** μ) as a function of x and y in global frame. There is **no** need for gradients; these values are calculated internally. On the other hand, if desired by the user, *FTire* can take into account a tangential or radial velocity of the surface, which is needed e.g. for the correct description of hydro-pulse or drum test rigs.

In contrast to other important tire models for ride-comfort, **no** pre-processing at all has to be performed on the original road profiles.

4. *FTire* Parameters

When calling *FTire* from within ADAMS™, model parameters are read from a file given in TiemOrbit format. Alternatively, *FTire* allows for several other formats, including TYDEX. The following is a complete list of all parameters the actual version of *FTire* uses as input data:

- **rolling circumference** under normal running conditions,

- **rim diameter,**
- **width of tread** that comes into contact with road under normal running conditions without camber angle,
- **tire overall mass**,
- exactly one out of:
  - **portion of tire mass that „moves“ with belt** (includes steel chord, tread rubber, and approximately half of side-walls, excludes remaining half of side-walls and bead), or
  - **tire radial stiffness** at very low loads on flat surface,
- increase of overall radial stiffness at high speed as compared to radial stiffness during stand-still, and wheel speed, at which this **dynamic stiffening** reaches half of the final value,
- percentage of **rolling circumference growth** at a running speed of 200 km/h, compared to low speed,
- **natural frequencies and respective damping moduli of first, second, and fourth vibration mode** of inflated, but unloaded tire with fixed rim, cf. fig. 4 (*remark*: the third mode is not needed because it is closely related to the fourth mode),
- exactly one out of:
  - **natural frequency of fifth mode** (in-plane bending), or
  - **belt in-plane bending stiffness** of inflated but unloaded tire, or
  - **tire radial stiffness** at very low loads, when being deflected on a cleat with prescribed geometry instead of a flat surface (cf. fig. 13),
- exactly one out of
  - **natural frequency of sixth mode** (out-of-plane bending), or
  - **belt out-of-plane bending stiffness** of inflated but unloaded tire,
- **tread depth** = mean groove depth in tread
- **rubber height over steel belt for zero tread depth** = distance between steel belt and grooves
- **stiffness of tread rubber** in Shore-A,
- **percentage of net to gross contact area** (**„tread pattern positive“**)
  (the last four parameters together, after pre-processing, actually result in only two values used in *FTire*: compression and shear stiffness of the idealized „blocks” that represent tread rubber),
- quotient of **tread rubber damping modulus** and tread rubber elasticity modulus (*remark:* deflection/force phase-lag of elastomers is said to be independent on excitation frequency. This behavior is not yet implemented in *FTire*; instead, viscous damping is used so far),
- coefficients of **maximum friction** and **sliding friction** that occurs between tread rubber and road, both at very low, at moderate, and at very high ground pressure values.

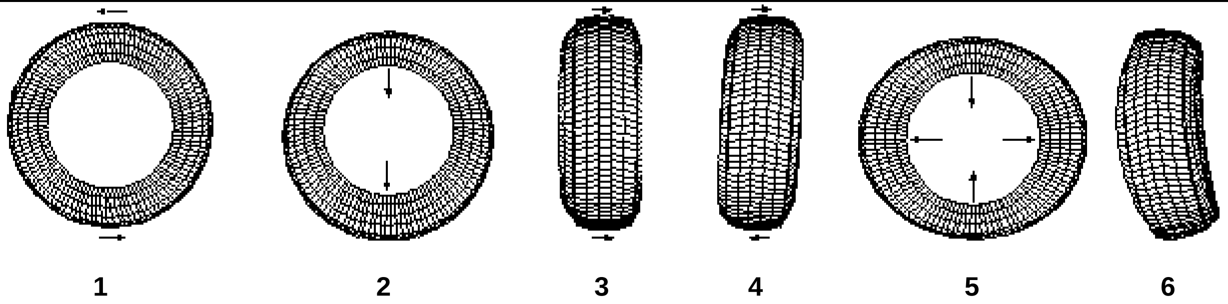


Fig. 4: First six vibration modes of an unloaded tire with fixed rim

Apparently, there are different combinations of parameters possible that all completely determine the structural stiffness and damping properties of *FTire*. The choice of these data might depend on the kind of measurements that are available, or cheap, or accurate enough. Note that all modal data are only used to calculate spring stiffnesses and damping coefficients such that the mathematical model, for small excitations, shows exactly the measured behavior in frequency domain. *FTire* is **not** a modal model, nor is it linear.

When parameterizing *FTire*, it turns out that the bending mode frequencies rather sensitively influence the respective bending stiffness. As an alternative, determining the radial stiffness both on flat surface and on a short obstacle (cleat) is a cheap and very accurate way to get both the vertical stiffness between belt nodes and rim, and the in-plane bending stiffness (cf. fig. 13).

Unfortunately, there is no direct analogy of the above procedure to get the out-of-plane bending stiffness, too. But this parameter seems to be not as relevant for ride comfort and durability as the in-plane bending stiffness. One indirect, but also very accurate way at least to validate the out-of-plane bending stiffness is to check the resulting side force characteristic. The difference between maximum side force and side force for very large side-slip angles is very sensitively determined both by the tread rubber friction characteristic, and by the out-of-plane bending stiffness. Similarly, the fourth mode (cf. fig. 4), being itself determined by the stiffness between belt nodes and rim in lateral direction, very strongly influences the side-slip angle where maximum side force occurs.

The procedure to parameterize *FTire* might look as follows:

1. Get **rolling circumference**, **rim diameter**, **tread width**, **tire mass**, **tread depth**, **rubber height over steel belt**, **shore-A stiffness of tread rubber**, **and tread pattern positive** either from tire data sheets, or by some simple and cheap measurements, or directly from the tire supplier.

2. Determine **natural frequencies** and **damping moduli** of the first 6 modes, for an unloaded, inflated tire, where the rim is fixed. Normally, this is done by exciting the tire structure with an impulse hammer, measuring the time histories of at least 4 acceleration sensors in all three directions, distributed along the tire circumference, and process these data by means of an FFT signal analyzer.

3. Determine the tire **radial stiffness** on flat surface and on a short obstacle.

4. Determine (or estimate) **tread rubber adhesion and sliding friction coefficients** for ground pressure values 0.5bar, 2bar, and 10bar.

5. Take natural frequencies and damping moduli of **modes # 1, 2, and 4**, together with **the radial stiffness on flat surface and on a cleat**, as well as the remaining basic data. These values result in a first, complete *FTire* input file.

6. Let *FTire* pre-process these data. **Compare** the resulting additional modal properties of the model with that modal data that are not used so far (**modes # 3, 5, 6**). If necessary, adjust the pre-processed data to find a compromise, regarding accuracy.

7. If respective measurements are available, **validate** the data determined so far by means of **side force and aligning torque characteristics,** and by measurements of vertical and longitudinal force variations induced during **rolling over cleats** both with low and high speed (cf. figs. 5 to 12).

The author is very much aware of the fact that this procedure might sound more simple than it is in practice. On the other hand, every tire model that is accurate enough for ride comfort and durability calculations will need similar or even more data.

To facilitate parameterization in the future, a new tool „*TIRE/calc*“ is being under development and nearly finished. This tool calculates all static and modal data used in *FTire* by means of a detailed FE model. In turn, this FE model only takes geometry data and material properties of all tire components, like carcass and belt layers, bead rubber, bead wire, tread, and so on. For those users that have access to these tire design data, the new approach might become promising. In the end, it is planned to establish a CAE process chain that takes tire design data and directly results in the prediction, or at least rough estimation, of handling and ride comfort characteristics.

Kernel of *TIRE/calc* is the FE tire model *DTire* (cf. fig. 4), together with a static but refined new version (cf. [2] and [4]). Using these models, a list of relevant load cases is automatically processed by *TIRE/calc*, describing tire deflections in several directions and magnitudes, as well as natural frequencies and damping moduli of all relevant modes. First experiments show that the whole process of estimating the structural stiffness data of *FTire* for two different inflation pressure values will take **far less than 3 minutes** on a standard PC.

Another approach under investigation is even much faster, but still must be proven to be feasible and accurate enough. The idea: directly take the linearized stiffness and damping matrix of *DTire*, perform appropriate static condensation to meet the *FTire* „grid“, and identify those few stiffness and damping values of *FTire* that exactly reproduce the condensed matrices.

5. *FTire* Performance

In table 1, some typical CPU time measurements, obtained during stand-alone *FTire* simulations, are put together. The measurements have been performed on

- a single-processor Pentium III 500Mhz PC, Windows NT 4.0/SP5, Visual Fortran 6.0, Visual C++ 6.0;
- the same machine, with Linux (kernel 2.2.3) and Gnu Fortran, Gnu C++.

Note that all pre-processing calculations need to be performed only if tire data have changed. If a vehicle dynamics model is equipped with identical tires, of course pre-processing also has to be performed only once. If pre-processed data are available, which is automatically recognized by *FTire*, they are directly read from file, instead of the basic data. In addition, for the convenience of the user, a tool will be available that enables pre-processing outside ADAMS/Solver™. By this, it is achieved that ADAMS™ simulations immediately start running, without waiting for the results of *FTire* pre-processing.

The actually needed number of belt elements (= belt segments) and blocks per belt element of course depends on the demands on accuracy and on the shortest wavelengths contained in the road profile. For example, the combination 60 elements + 10 blocks per element has a longitudinal road profile resolution of approximately 3 mm, whereas 120 elements + 40 blocks per element resolves road unevenness even below 1 mm. Similarly, the internal time-step depends on the desired resolution in time domain. With Δt = 0.4 ms, a (theoretical) resolution of 250 Hz is achieved, where at least 10 time-steps per period are calculated. *FTire* can be invoked with relatively large external time-steps without causing numerical instability, because it uses an internal, refined time-step that is chosen constant as long as possible.

Platform: Pentium III 500 MHz	CPU time for pre-processing		CPU time for 1 s simulation of a single tire	
	NT	Linux	NT	Linux
60 segments, block distance 3 mm, Δt = 0.4 ms	**2.57**	**14.22**	**5.55**	**6.05**
60 segments, block distance 0.75 mm, Δt = 0.4 ms	**2.95**	**14.26**	**9.68**	**9.68**
120 segments, block distance 0.75 mm, Δt = 0.4 ms	**8.58**	**38.06**	**16.95**	**18.32**
60 segments, block distance 3 mm, Δt = 0.2 ms	**2.57**	**18.37**	**11.00**	**12.45**
60 segments, block distance 0.75 mm, Δt = 0.2 ms	**2.95**	**20.55**	**17.82**	**20.91**
120 segments, block distance 0.75 mm, Δt = 0.2 ms	**8.65**	**48.51**	**33.82**	**38.76**

Table 1: Typical CPU time requirements of *FTire*

6. Future Expansions

The next major steps to improve *FTire* will be

- complete, optimize, and release ***TIRE/calc*** (cf. chapter 4) for the calculation of *FTire* structural data directly from CAD data and material properties data bases. This is done to replace or complement measurements of static and modal properties;

- expand *FTire* towards a true, downward compatible 3D model, by taking into account the lateral width of steel belt and tread. This is important in situations where obstacles do have only short extensions or wave lengths in **lateral** direction, or where cleats are oriented in an **oblique direction** relative to the tire's travel path.

  Two different approaches for this expansion will be compared.

  The **first approach** is to use several rings of belt segments, instead of only one. The nodes of these rings will be coupled by additional spring/damper elements in lateral or oblique direction.

  The **second approach** is to continue using only one ring, but providing an additional degree of freedom for the nodes. This additional degree of freedom will be rotation around an axis in circumferential direction. Tread blocks then will be scattered over **areas** between two adjacent belt nodes, rather than along the connecting lines. Position and orientation of these areas are determined by the position of the respective belt nodes, together with their degree of freedom of rotation.

Clearly, the first approach seems to be more accurate. The final decision, however, on the modelization refinement will be made by looking for the best compromise between accuracy **and** speed of computation.

7. Sample simulation results

To demonstrate the wide applicability of *FTire*, and to show the quality of results that can be achieved even in very delicate maneuvers, some results are put together in figures 5 to 12.

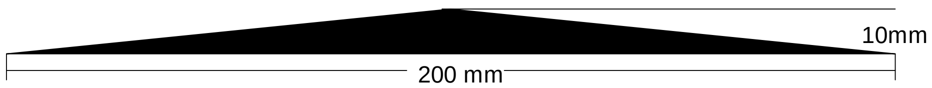
Please note that highest accuracy in **handling** characteristics had not been primary goal for *FTire.* Nevertheless, figures 7 to 12 indicate a qualitatively satisfactory behavior not only in pure longitudinal or side-slip situations, but also with combined slip, large camber angles, etc. Of course, the accuracy could be improved. This holds especially for the side force characteristics, where the difference between maximum and sliding value seems to be a bit too large. As mentioned above, this fact might indicate that the out-of-plane bending stiffness is too large. So far, no parameter fit procedure has been applied yet.

But, in contrast to simple empiric handling models that mathematically describe steady-state measurements, *FTire* will calculate these forces accurate enough even in rapidly changing, transient situations or on short-waved road irregularities.

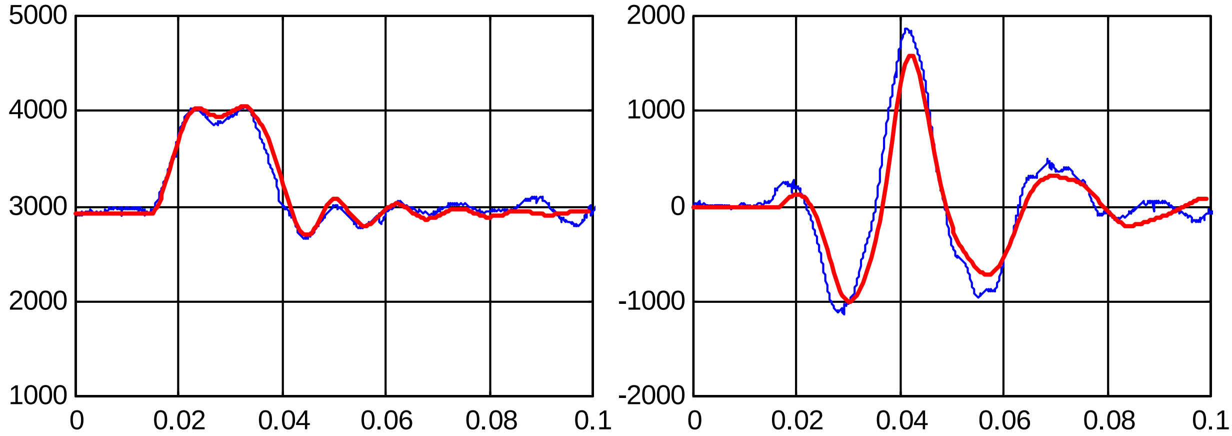
This is illustrated by figures 5 and 6. Both compare wheel load and fore-aft force during rolling over two different kinds of obstacles, with respective measurements. The results look quite similar to those obtained with the far more complex and time consuming tire model *DTire* mentioned above. Especially the case v = 120 km/h is a hard nut to crack for tire models. Remember: for an obstacle length of 20 mm, each block that comes into contact only rests about 3 ms on the obstacle, depending on the foot-print length.

A well-known, but nevertheless very interesting feature can be seen in nearly all measurements: in the very first moment of contact, the obstacle seems to „attract“ the tire. This is the result of a positive longitudinal force over a short period of time. That force, in turn, is caused by the portion of the belt in front of the wheel. This portion is swelled outwards when hitting the obstacle, and thus pulling the rim in forward direction at the very first moment.

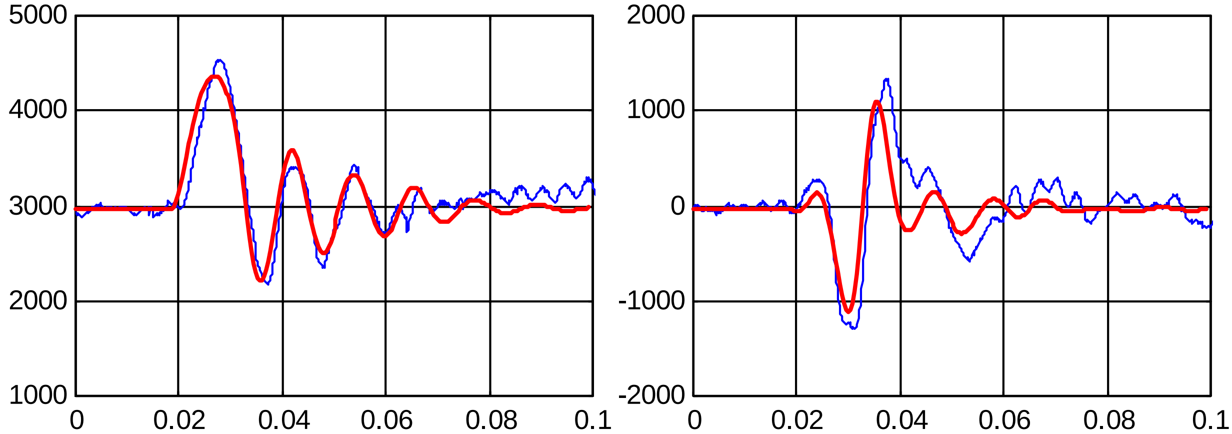
In principal, this behavior also is shown by *FTire*, especially for obstacles with sharp edges and at moderate speeds. But the quantitative value of this force is too small at medium speeds and gets completely lost for high speeds. The reason for this is still under investigation.



v = 40 km/h:



v = 80 km/h:



v = 120 km/h:

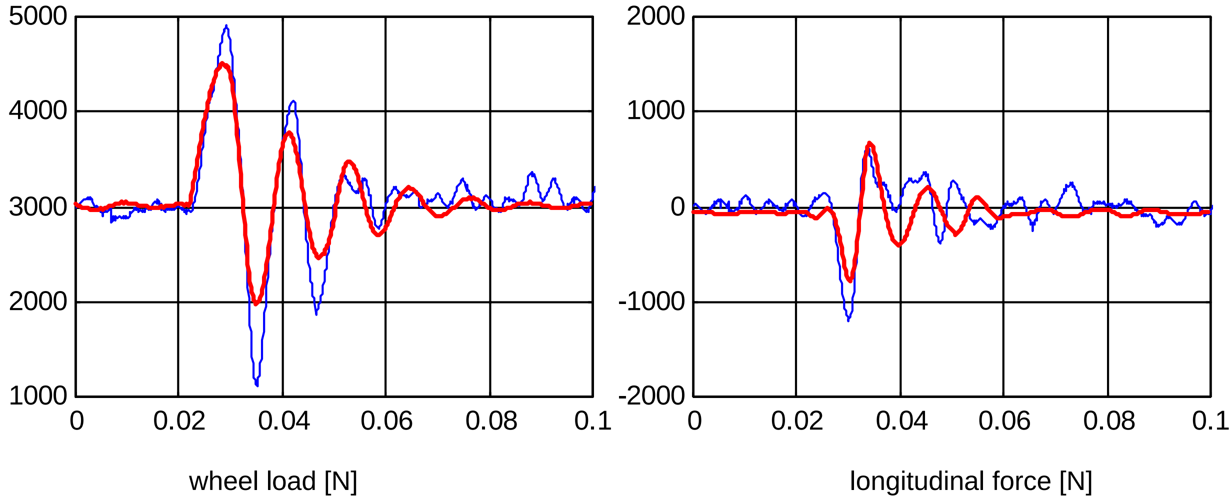


Fig. 5: Rolling over a flat, triangle-shaped obstacle (v = 40, 80, 120 km/h, fixed spindle)

simulation   measurement

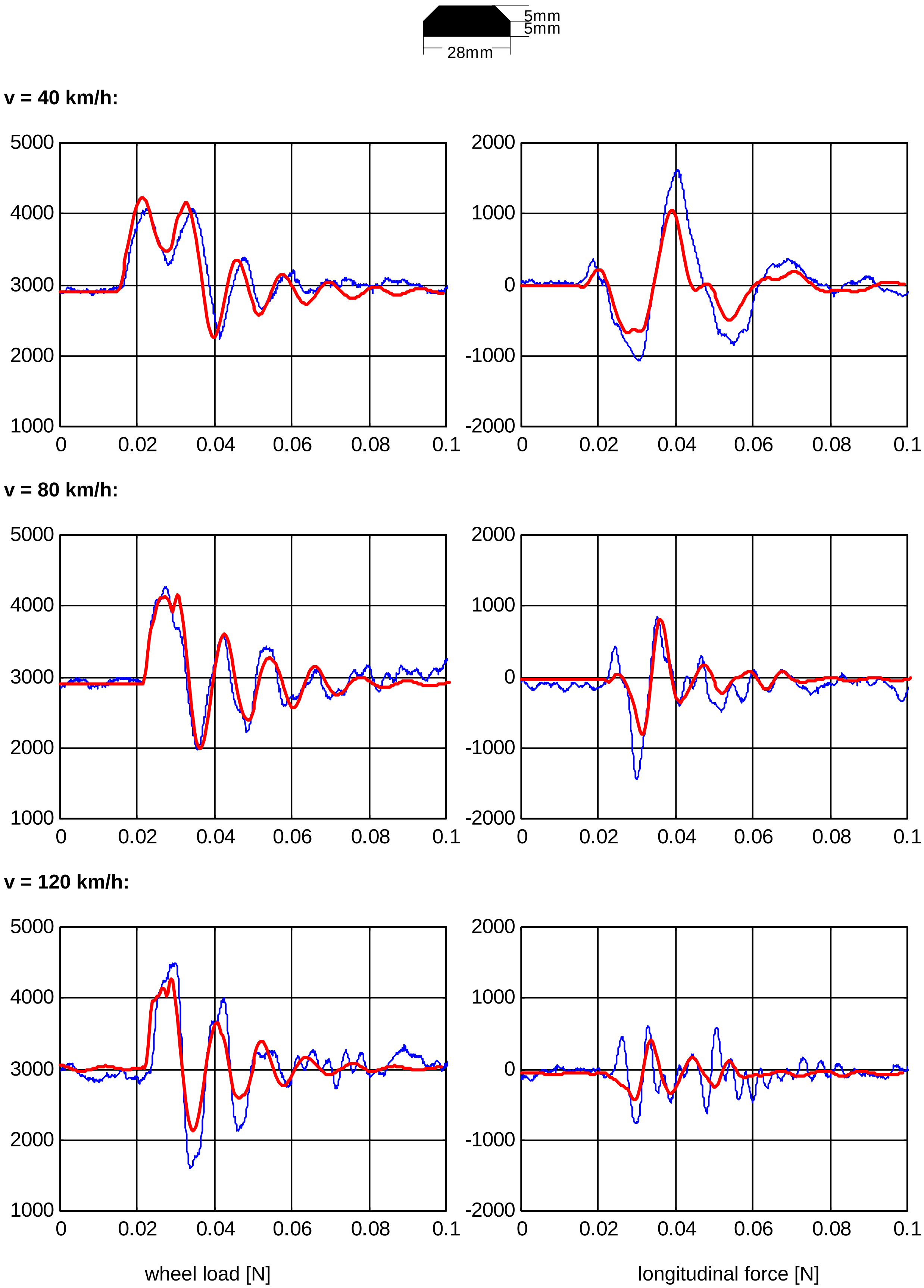


Fig. 6: Rolling over a cleat at different speeds (v = 40, 80, 120 km/h, fixed spindle)

simulation measurement

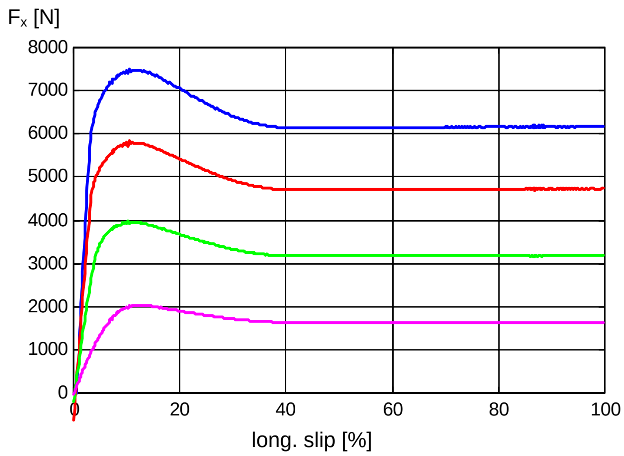


Fig. 7: Sample fore-aft force characteristics as calculated by *FTire*
(F_z = 2, 4, 6, 8 kN)

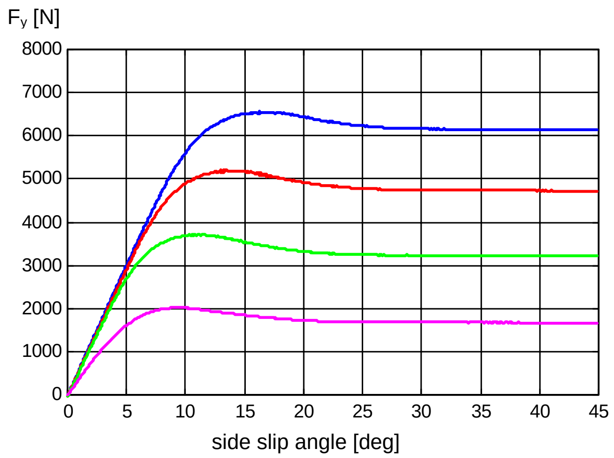


Fig. 8: Sample side force characteristics as calculated by *FTire*
(F_z = 2, 4, 6, 8 kN)

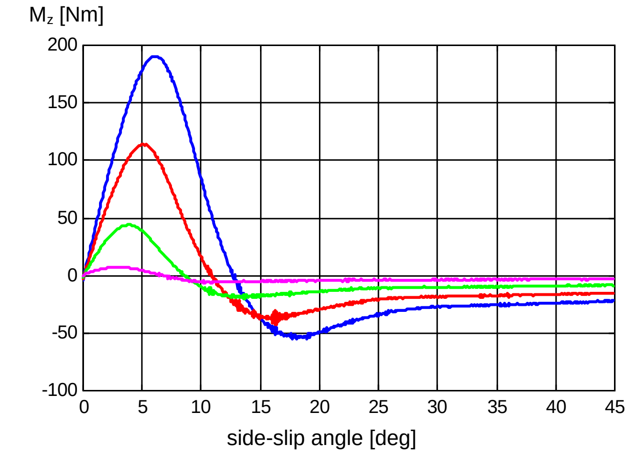


Fig. 9: Sample self-aligning torque characteristics as calculated by *FTire*
(F_z = 2, 4, 6, 8 kN)

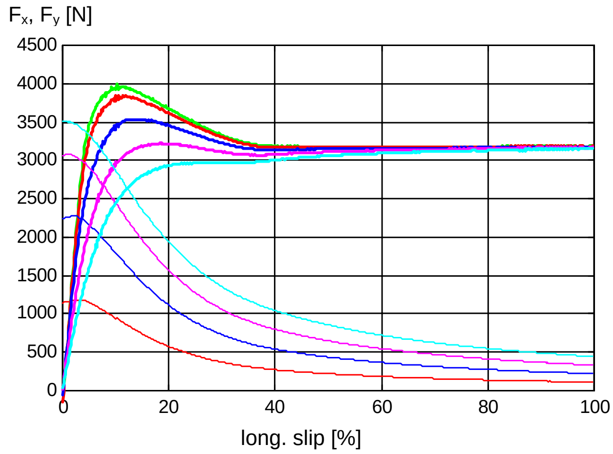


Fig. 10: Sample combined slip characteristics as calculated by *FTire*: F_x (bold lines) and F_y (thin lines) vs. long. slip (F_z = 4 kN, side-slip angle α = 0, 2, 4, 6, 8 deg)

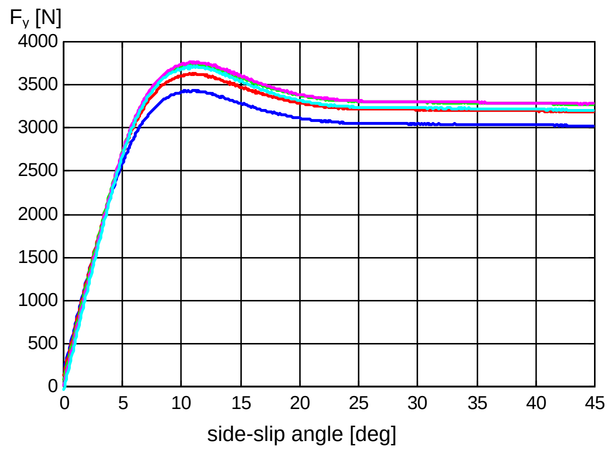


Fig. 11: Sample side force characteristics as calculated by *FTire*
(camber angle γ = 0, 2, 4, 6, 8 deg, F_z = 4 kN)

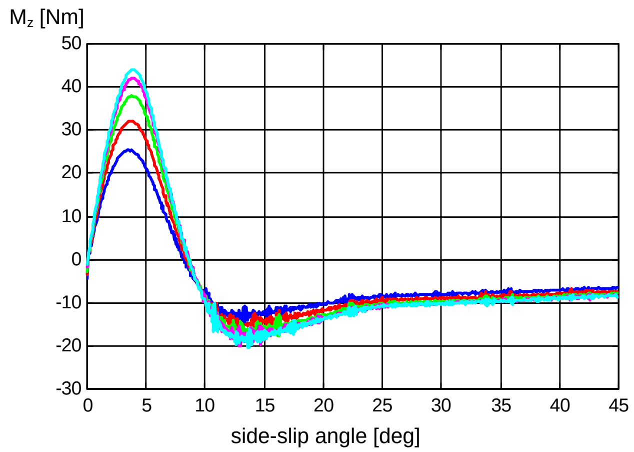


Fig. 12: Sample self-aligning torque characteristics as calculated by *FTire*
(camber angle γ = 0, 2, 4, 6, 8 deg, F_z = 4 kN)

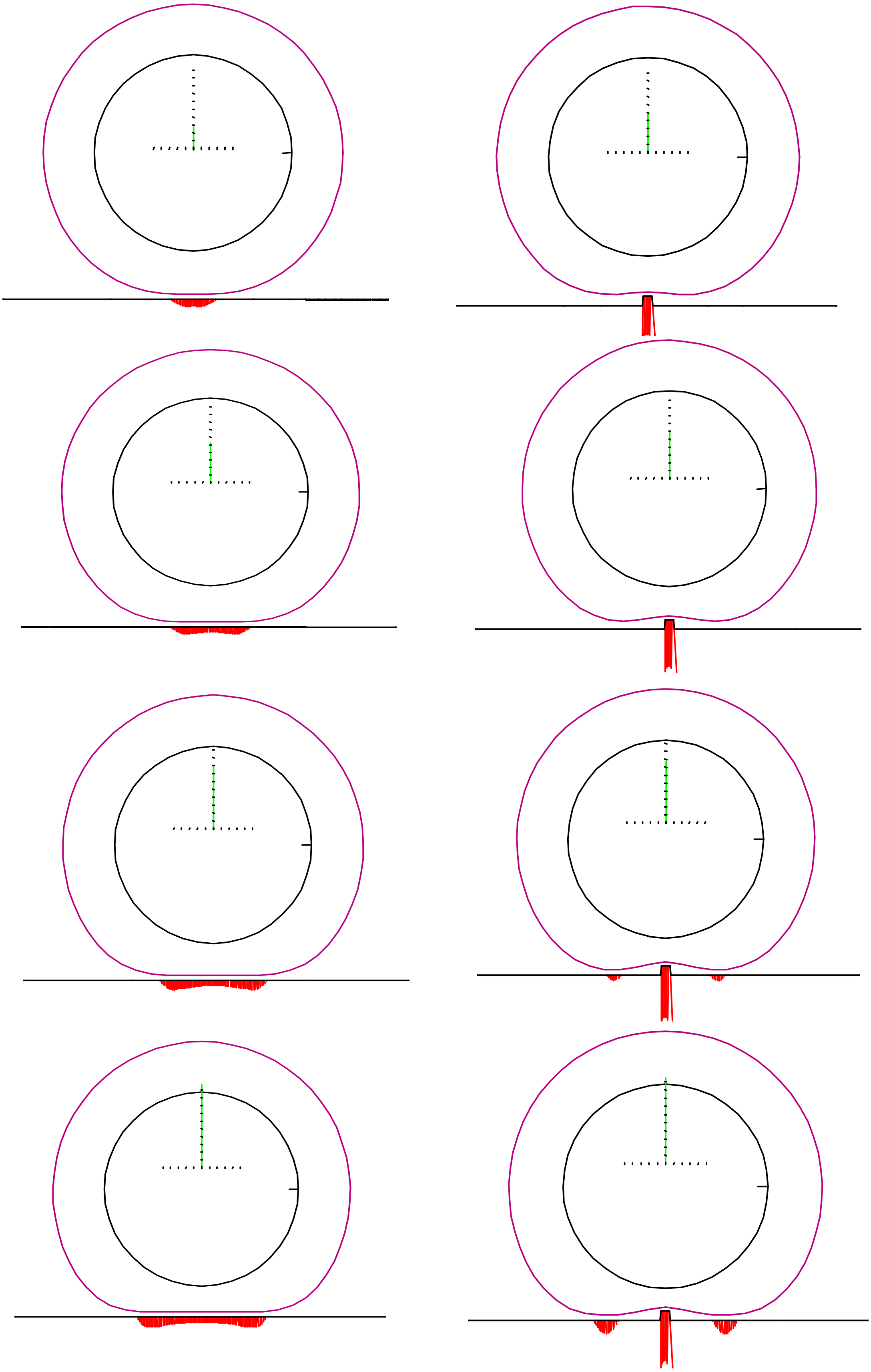


Fig. 13: Tire belt deformation and contact forces during radial stiffness characteristic simulation:
left column: on even surface, right column: on a small obstacle

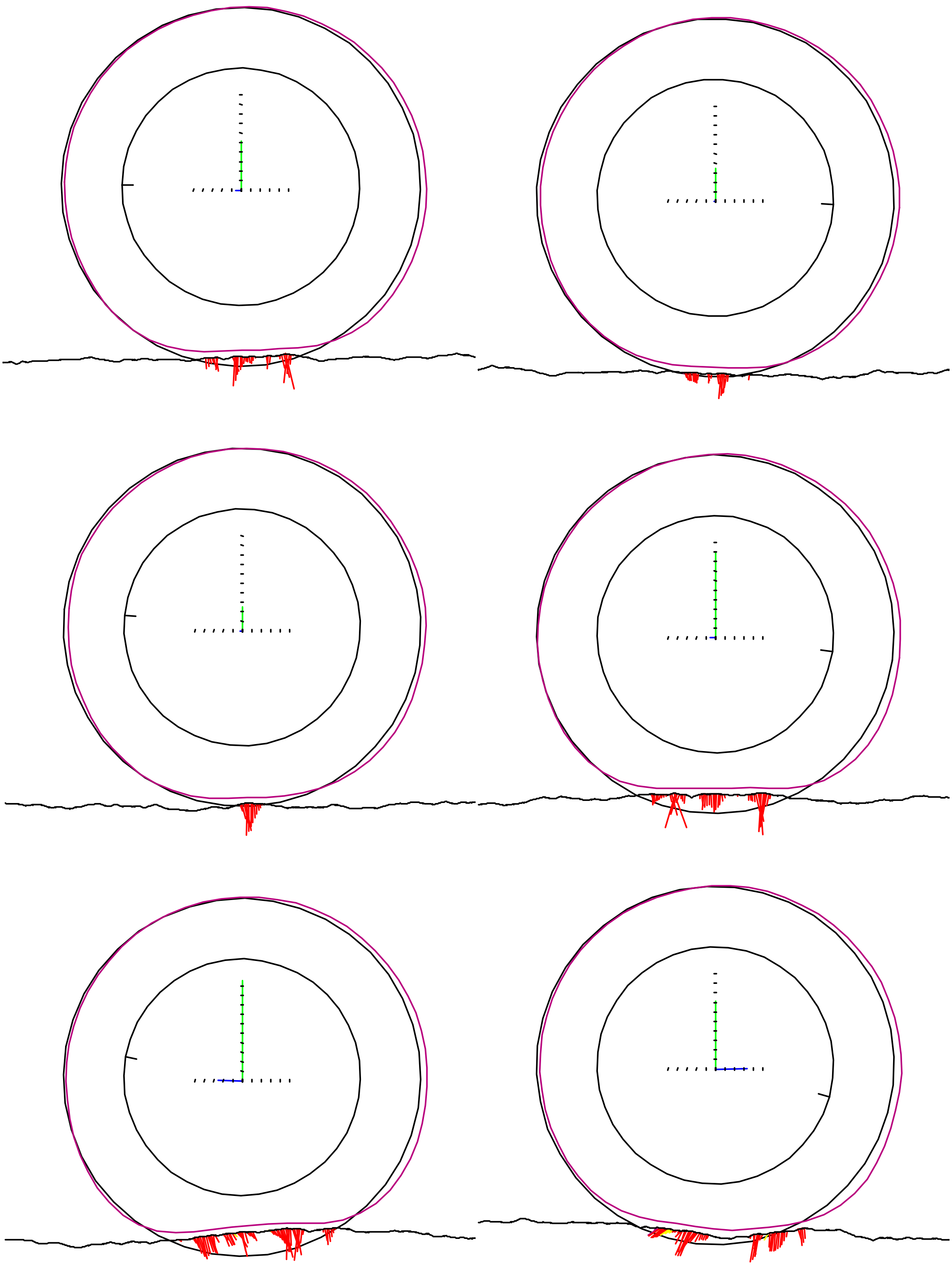


Fig. 14: Tire belt deformation and contact forces while rolling over extremely uneven road profile
(circular belt reference shape is plotted to illustrate actual belt deformation. v = 20 m/s, spindle height fixed)

Reference

[1] **Ammon, D., Gipser, M., Rauh, J., Wimmer, J.**: Effiziente Simulation der Gesamtsystemdynamik Reifen-Achse-Fahrwerk. In: Reifen, Fahrwerk, Fahrbahn. VDI-Berichte 1224. VDI Verlag 1995

[2] **Gipser, M.**: DNS-Tire, ein dynamisches, räumliches nichtlineares Reifenmodell. In: Reifen, Fahrwerk, Fahrbahn. VDI Berichte 650, p. 115-135. VDI Verlag, Düsseldorf 1987

[3] **Gipser, M.**: Zur Modellierung des Reifens in CASCaDE. Mitteilungen des Curt-Risch-Instituts der Universität Hannover. Hannover 1990

[4] **Gipser, M.**: DNS-Tire 3.0 - die Weiterentwicklung eines bewährten strukturmechanischen Reifenmodells. In: Darmstädter Reifenkolloquium, VDI-Berichte 512, p. 52-62. VDI Verlag Düsseldorf 1996

[5] **Gipser, M., Hofer, R., Lugner, P.**: Dynamical Tire Forces Response to Road Unevennesses. In: Tyre Models for Vehicle Dynamic Analysis. Supplement to Vehicle System Dynamics, Vol. 27. Swets&Zeitlinger Lisse 1997

[6] **Van Oosten, J.J.M, Unrau, H.J., Riedel, G., Bakker, E.**: TYDEX Workshop: Standardisation of Data Exchange in Tyre Testing and Tyre Modelling. In: Tyre Models for Vehicle Dynamic Analysis. Supplement to Vehicle System Dynamics, Vol. 27. Swets&Zeitlinger Lisse 1997

[7] **Gipser, M.**: Reifenmodelle für Komfort- und Schlechtwegsimulationen. In: Tagungsband zum 7. Aachener Kolloquium Fahrzeug- und Motorentechnik. IKA, RWTH Aachen und VDI 1998

[8] **Gipser, M.**: *FTire*, a New Fast Tire Model for Ride Comfort Simulations. International ADAMS User's Conference Berlin, Germany 1999