FTire, a New Fast Tire Model for Ride Comfort Simulations

Michael **Gipser**, Esslingen University of Applied Sciences, Germany

Abstract

The new tire model *FTire* (**F**lexible Ring **Tire** Model) serves as a sophisticated tire force element. It can be used in MBS models for vehicle ride comfort investigations, and other vehicle dynamics simulations on even or uneven roadways. Presumably, *FTire* will be available as a new ADAMS module in the near future.

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

1. Aims and Scope of *FTire*

FTire is designed as a ´2+1/2-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, including lateral direction. 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 comfort **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 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 and pot-holes,
- 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 one 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 movements 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-

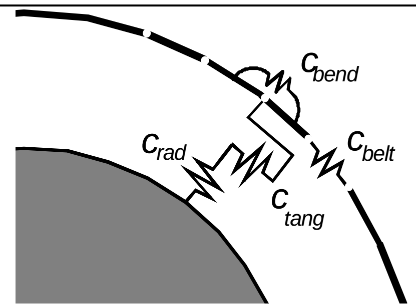

Fig. 1: Belt representation in *FTire*, in-plane part (simplified)

of-plane. The radial stiffness is refined by a parallel connection of a spring with a spring-damper series connection to allow for dynamic hardening of the overall tire radial stiffness at high wheel speeds;

- all stiffnesses, bending stiffnesses, and damping factors may be calculated during preprocessing, fitting prescribed modal properties, cf. the discussion of parameters below;

- to every belt element, a number (5 to 10, say) of mass-less 'tread ribs' is associated. These ribs carry nonlinear stiffness and damping properties in radial, tangential, and lateral direction. The radial deflections of the ribs 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 rib 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 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.

3. Implementation and Interfaces

FTire is fully implemented in standard Fortran 77, running on all important Unix platforms including Linux, as well as with Windows 95, 98, and NT. There are two interfaces available:

- a **time-discrete interface** that best fits to the internal structure of *FTire*. This interface, for example, is used in the DaimlerChrylser vehicle dynamics software CASCaDE, and in the Ford vehicle dynamics software VEDYNA. 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]. This interface had been defined to be used in commercial MBS-codes such as ADAMS™ and others. Again, this interface allows for several instances to be run simultaneously.

As far as ADAMS™ is concerned, the STI interface is considered only to invoke handling models with few state variables. So, following a recommendation of MDI, a combination of REQUEST / GFORCE statements, together with appropriate user-written interface subroutines GFOSUB and REQSUB, is used. At fixed time-steps, every millisecond, say, the rim rigid-body states are retrieved from the ADAMS model and fed into *FTire*, which integrates its own state variables, using multi-rate integration with a local time step (0.1 .. 0.5 ms, say). The resulting rim forces and moments are written to a COMMON block and applied to the ADAMS model as general forces and moments via GFORCE / GFOSUB.

This approach, working with the time-discrete version of the *FTire* interface, is implemented also for several other tire models of the author, that have the same interface. It runs very satisfactorily in several completely different applications.

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 frame,
- **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.

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.

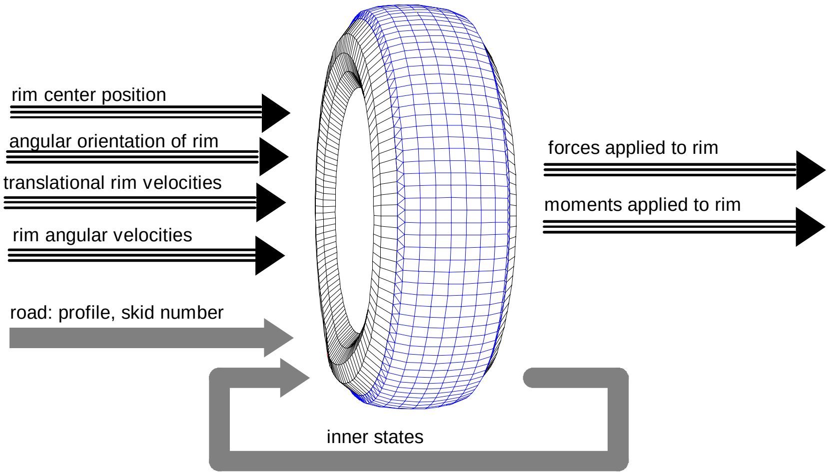

Fig. 2: Input/output behavior of the standard time-discrete interface

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

Alternatively, *FTire* can be caused to also integrate the rim rotation with respect to the hub-carrier. In this case, not the rigid body states of the rim, but that of the **hub-carrier** are the inputs, together with the driving and the maximum absolute braking torque. The output torque vector then does not contain the share in the direction of the wheel rotation. *FTire* eventually modulates the braking torque, if the wheel is blocked, in order to exactly maintain this blocking as long as it is necessary.

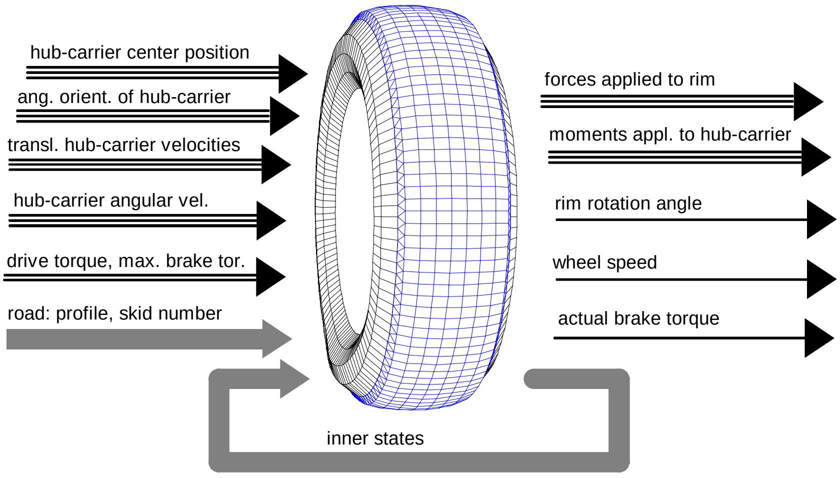

Fig. 3: Input/output behavior of the enhanced time-discrete interface

In addition to the above mentioned *FTire* interfaces to be called by ADAMS™ or other 3rd-party vehicle models, a stand-alone simulation environment *FTsim* for both NT and Unix is available. This simulation environment comes with a comfortable rim movement and road profile description facility, a vivid online animation using OpenGL™, and plot data output in many different formats, including Excel™, Matlab™, $Matrix_x$™, CASCaDE/Iplos, Gnuplot, and others.

The **road profile** or road surface, resp., is fed into *FTire* via a very general and simple interface, for which several implementations already exist. One of these implementations is the STI recommendation for road surface description used in the TYDEX interface (cf. [6]). For 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 some other tire models for ride-comfort, **no** pre-processing at all has to be performed on the original road profiles.

4. *FTire* Parameters

The following is a complete list of all parameters the actual version of *FTire* needs as input:

- **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**,

- one out of:
  - **portion of tire mass that 'moves' with belt** (includes steel chord, tread rubber, and half of side-wall, excludes remaining half of side-wall and bead), or
  - **tire radial stiffness** at very low loads,

- 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),

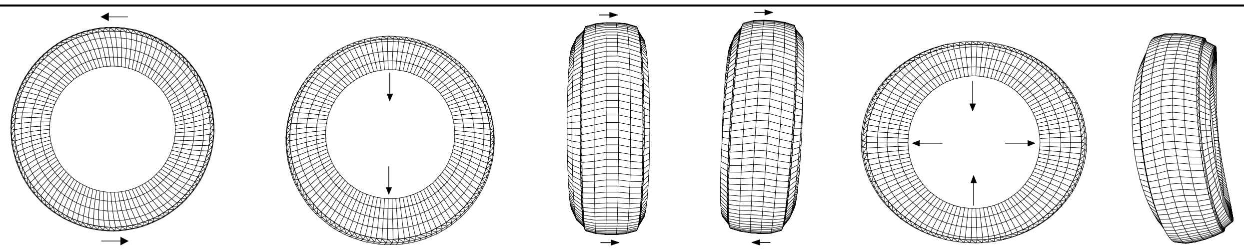

Fig. 4: First six vibration modes of an unloaded tire with fixed rim

- one out of:
  - **natural frequency of fifth mode** (in-plane bending), or
  - **belt in-plane bending stiffness** of inflated but unloaded tire,

- one out of
  - **natural frequency of sixth mode** (out-of-plane bending), or
  - **belt out-of-plane bending stiffness** of inflated but unloaded tire,

- **profile height** = mean groove depth in tread
- **rubber height over steel belt for zero profile height** = distance between steel belt and grooves
- **stiffness of tread rubber** in Shore-A,
- **percentage of contact area with respect to overall footprint area**,
- 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),
- sum of the **moments of inertia of rim and other rotating parts** without tire, with respect to wheel spin axis (*remark*: this parameter is only needed and used if rim rotation is integrated inside *FTire*),
- coefficients of **maximum friction** and **sliding friction** that occurs between tread rubber and road, both at very low and at very high ground pressure values.

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 5.0, Visual C++ 5.0;
- 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 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.

The actually needed number of belt elements (= belt segments) and ribs 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 ribs per element has a longitudinal road profile resolution of approximately 3 mm, whereas 120 elements + 40 ribs 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 far as possible.

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

Table 1: CPU time requirements of *FTire*

6. 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 can and should be improved. This holds especially for the side force characteristics, where the difference between maximum and sliding value 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 highly instationary situations or on short-waved road irregularities.

This is illustrated with 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*, cf. [4]. Especially the case v = 120 km/h is a hard nut for tire models. Remember: for an obstacle length of 20 mm, each rib 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. 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; any clarification will probably lead to a further improvement of *FTire*.

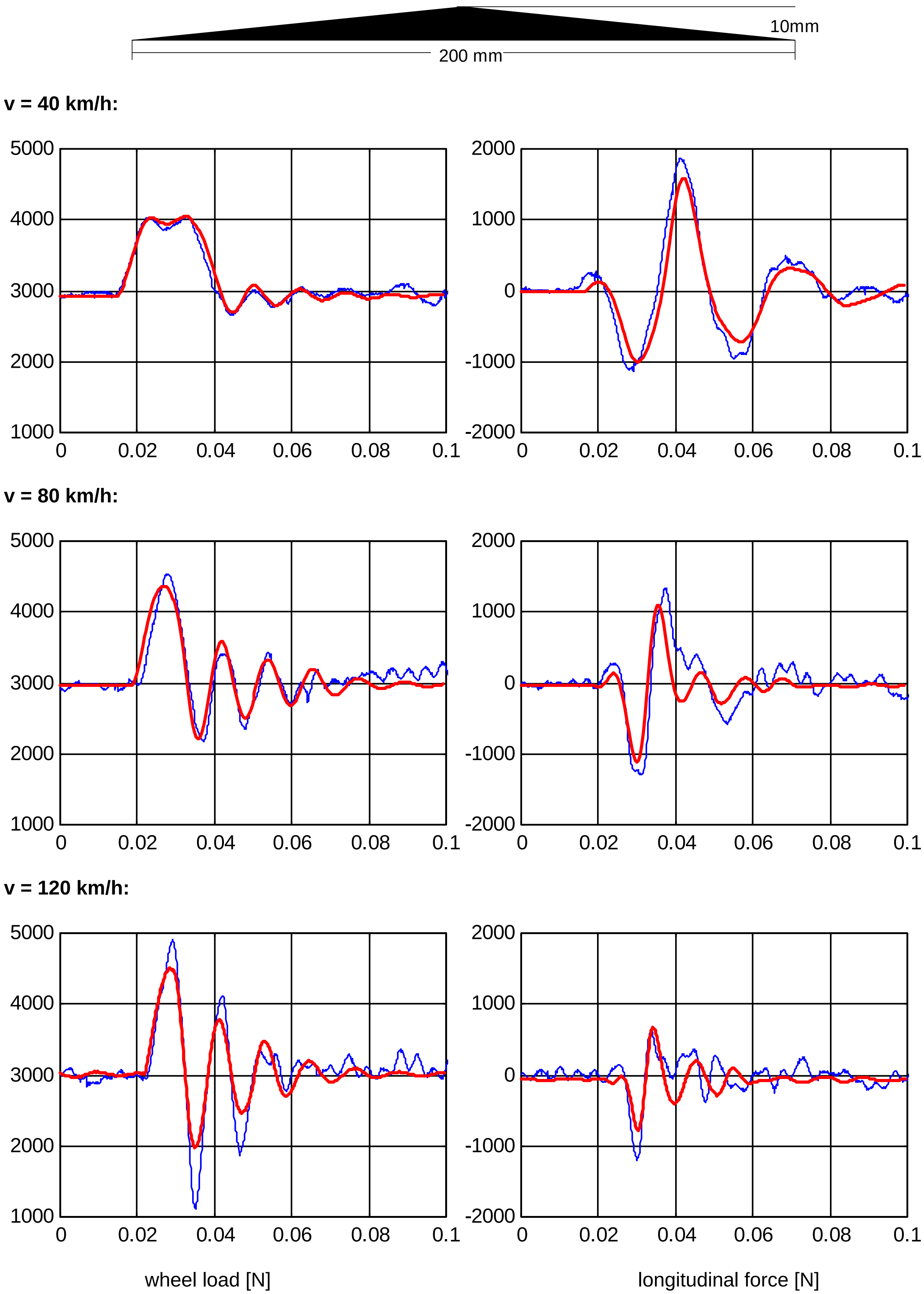

Fig. 5: Rolling over a flat, triangle-shaped obstacle (v = 40, 80, 120 km/h, fixed spindle)

simulation measurement

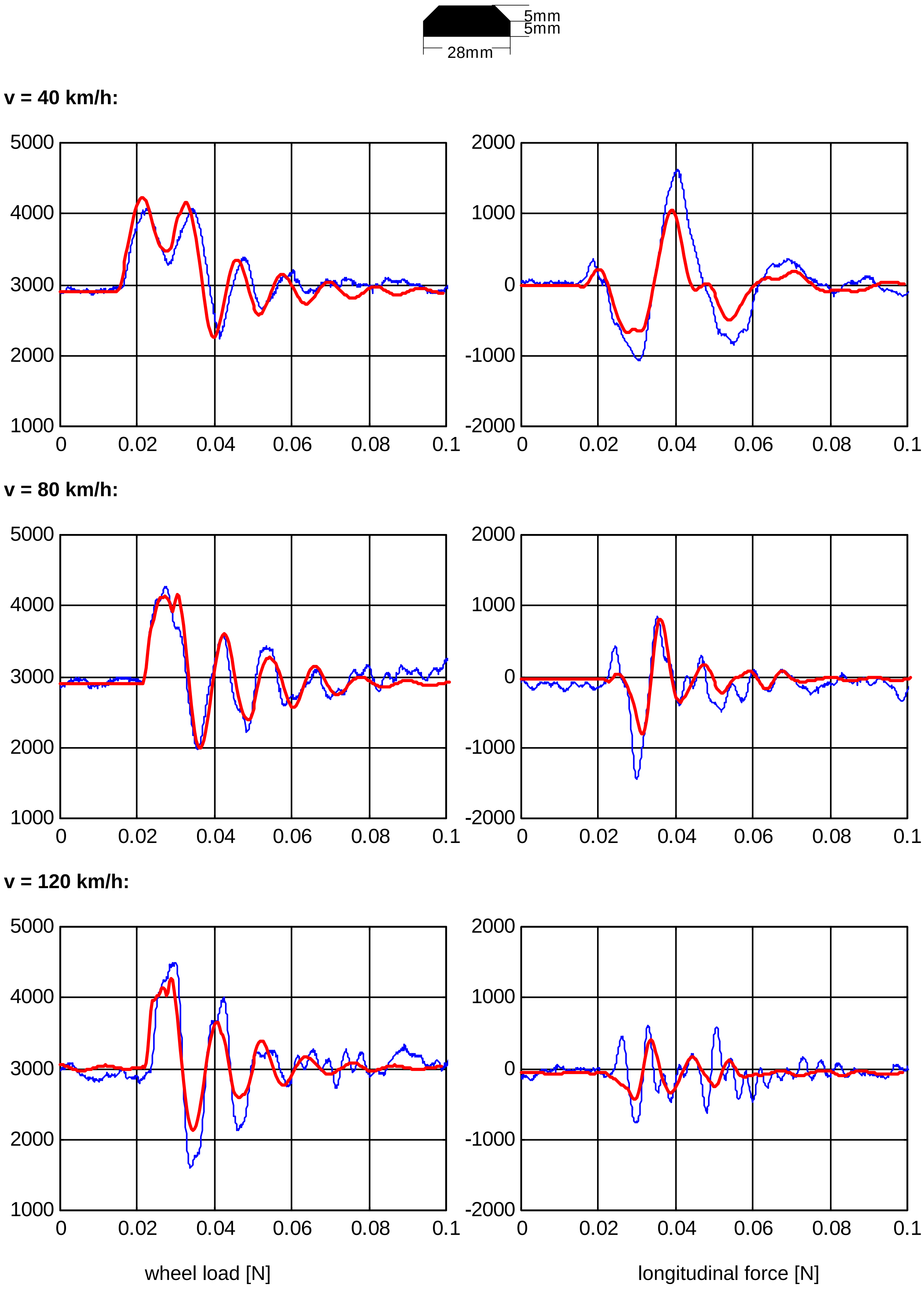

Fig. 6: Rolling over a cleat at different speeds (v = 40, 80, 120 km/h, fixed spindle)

simulation   measurement

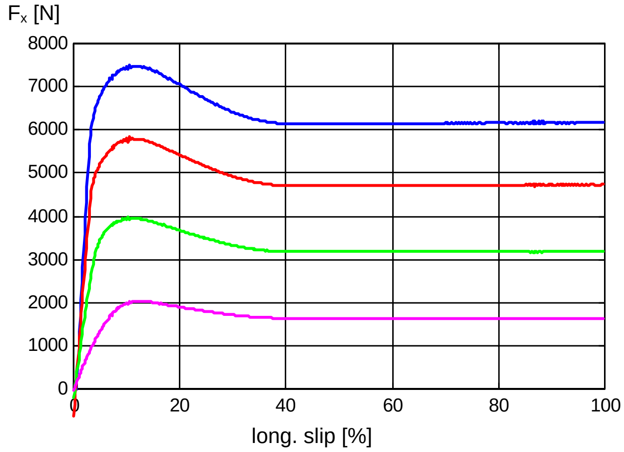

Fig. 7: Sample fore-aft force characteristics as calculated by *FTire*
(F_z = 2, 4, 6, 8 kN)

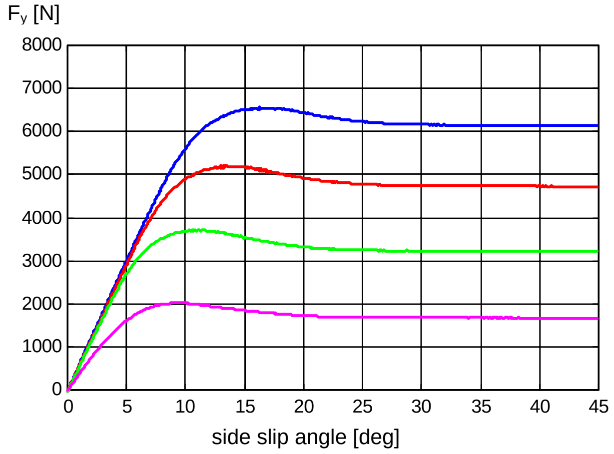

Fig. 8: Sample side force characteristics as calculated by *FTire*
(F_z = 2, 4, 6, 8 kN)

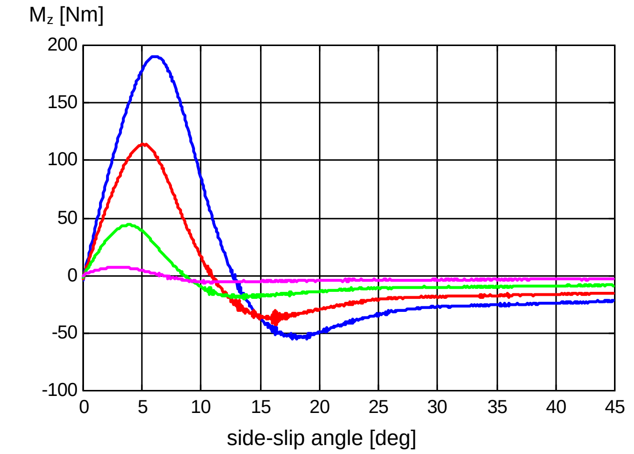

Fig. 9: Sample self-aligning torque characteristics as calculated by *FTire*
(F_z = 2, 4, 6, 8 kN)

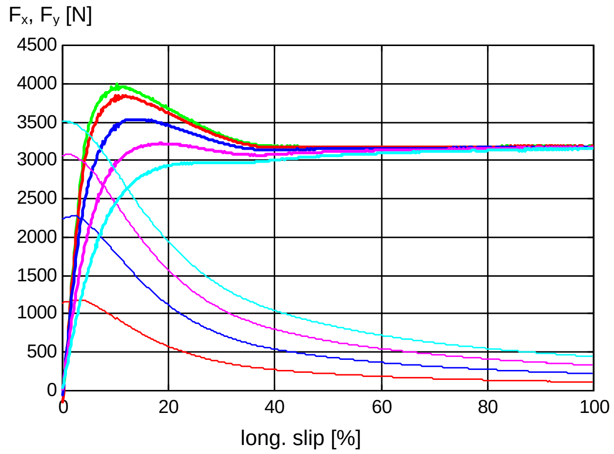

Fig. 10: Sample combined slip characteristics as calculated by *FTire*: F_x (bold lines) and F_y (thin lines) vs. long. slip (F_z = 4 kN, side-slip angle α = 0, 2, 4, 6, 8 deg)

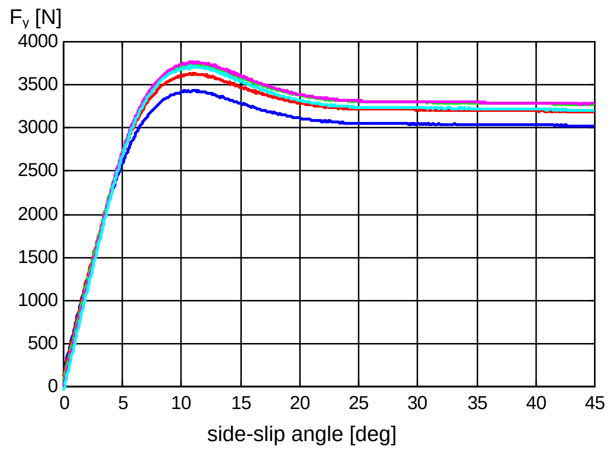

Fig. 11: Sample side force characteristics as calculated by *FTire*
(camber angle γ = 0, 2, 4, 6, 8 deg, F_z = 4 kN)

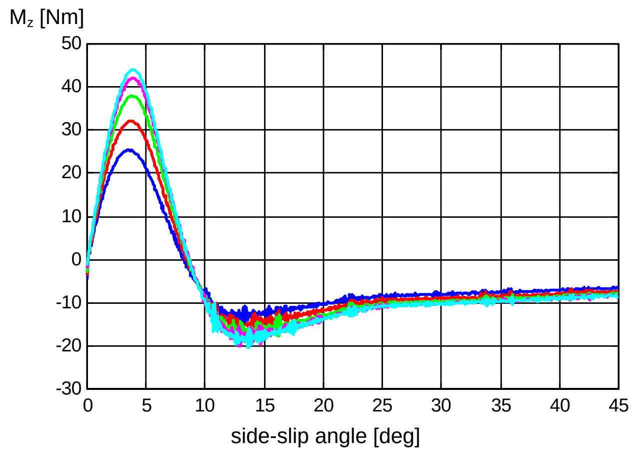

Fig. 12: Sample self-aligning torque characteristics as calculated by *FTire*
(camber angle γ = 0, 2, 4, 6, 8 deg, F_z = 4 kN)

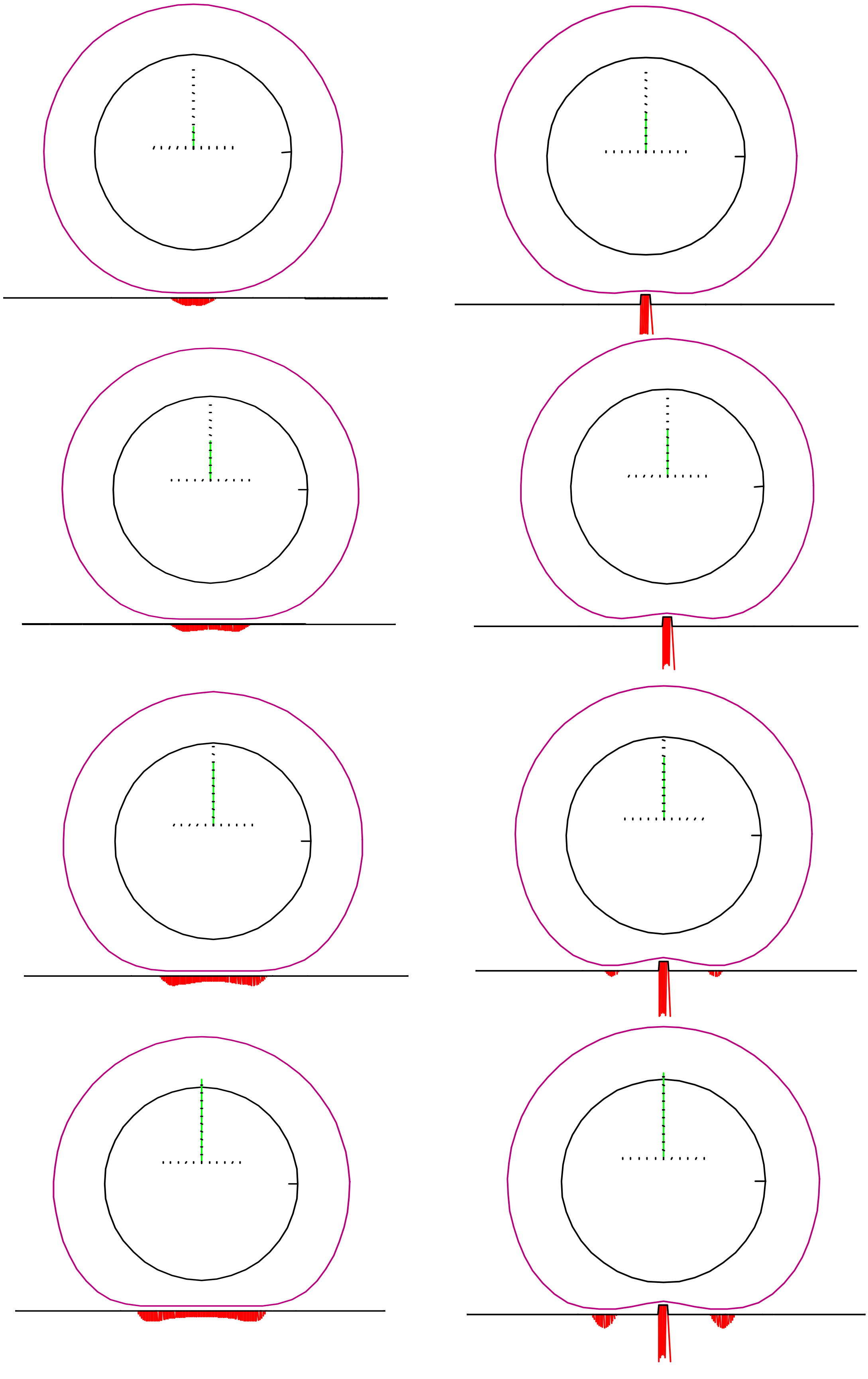

Fig. 13: Tire belt deformation and contact forces during radial stiffness characteristic simulation:
left column: on even surface, right column: on a small obstacle

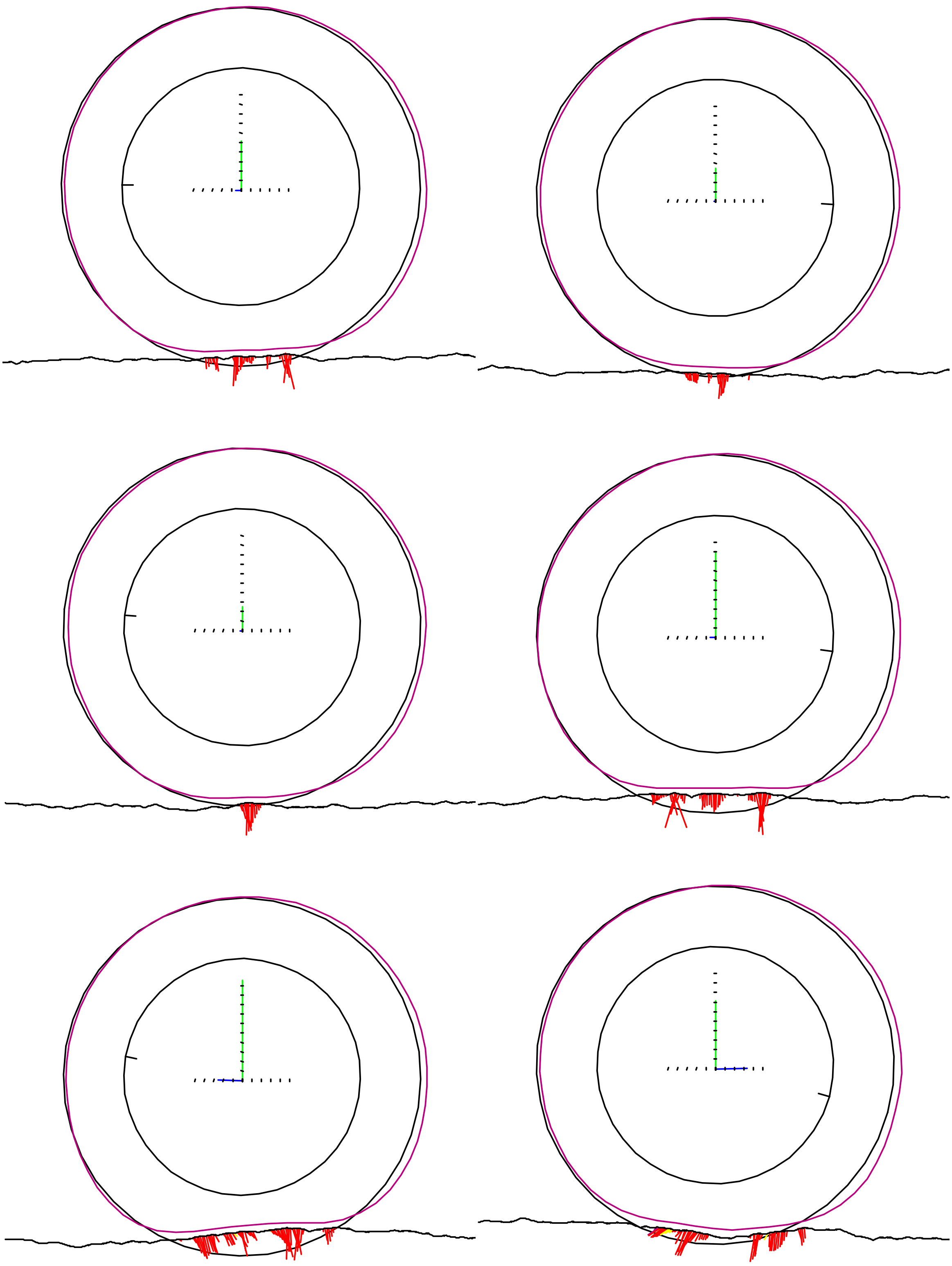

Fig. 14: Tire belt deformation and contact forces while rolling over extremely uneven road profile
(circular belt reference shape is plotted to illustrate actual belt deformation. v = 20 m/s, spindle height fixed)

Literature

[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