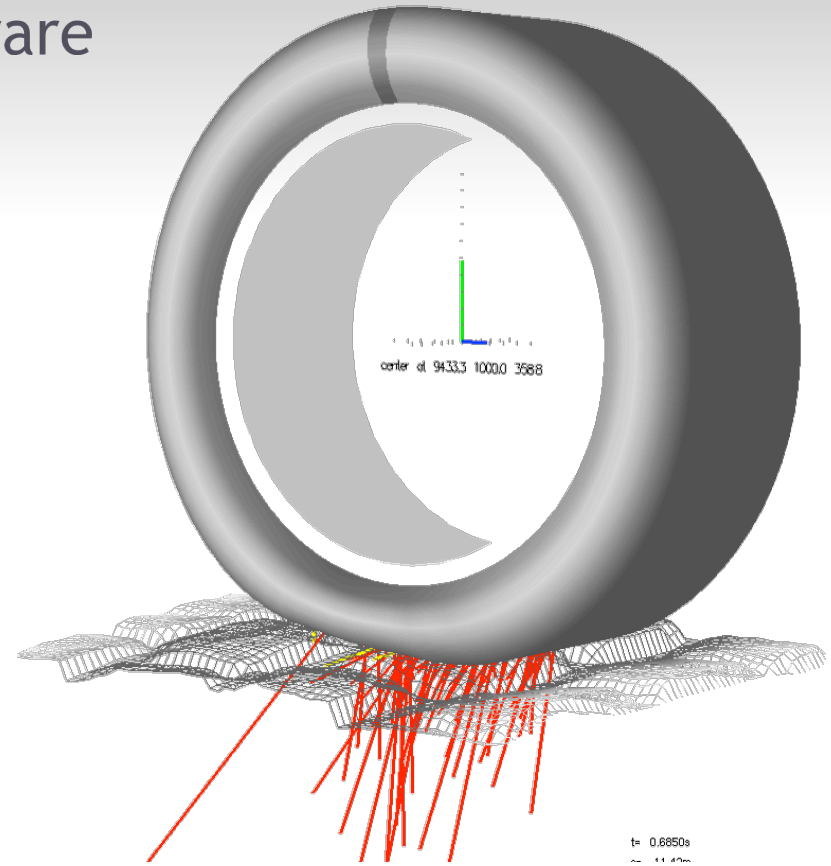
cosin
scientific software



FTire: a Physically Based Tire Model for Handling, Ride, and Durability
Part 2: Modelization

Michael Gipser
Esslingen University of Applied Sciences
& cosin scientific software

- ✓ Tire/road induced vibrations up to 150..200 Hz
- ✓ Vibration excitation through tire imperfections
- ✓ Generation of load histories for durability simulations
- ✓ Traction & handling on extremely uneven roads
- ✓ Rolling resistance
- ✓ Tire misuse
- ✓ Run flat
- ✓ Tread wear
- ✓ Steering torque amount when parking
- ✓ Assessment of highly dynamic suspension control systems
- ✓ Moving ground; all kinds of test-bench simulations
- ✓ Non-rigid surface and soft soil simulations
- ✓ Race cars, motorcycles, trucks, aircrafts, earth mover, etc.
- ✓ Non-Rigid surface and soft soil

- × Detailed stress prediction in belt/carcass structure
- × Hydroplaning
- × Noise
- × … and of course much more

- fully non-linear 3D model, working in time domain
- valid up to 150..200 Hz both in-plane and out-of-plane
- longitudinal and lateral wave lengths down to 1 cm
- sharp-edged obstacles
- parameterization as simple and flexible as possible
- usage of 'easy-to-measure' static, steady-state, and modal properties
- computing time 1 .. 20 * real time
- valid for ride and handling, both in steady-state and dynamic conditions
- simple and flexible interfacing to vehicle and road models
- wide variety of assisting tools

Two main model parts

Tire structure

bead, carcass, belt: sub-divided into 90..360 belt segments connected to each other and to rim by non-linear, pressure-dependent distributed stiffness and damping elements

Tread

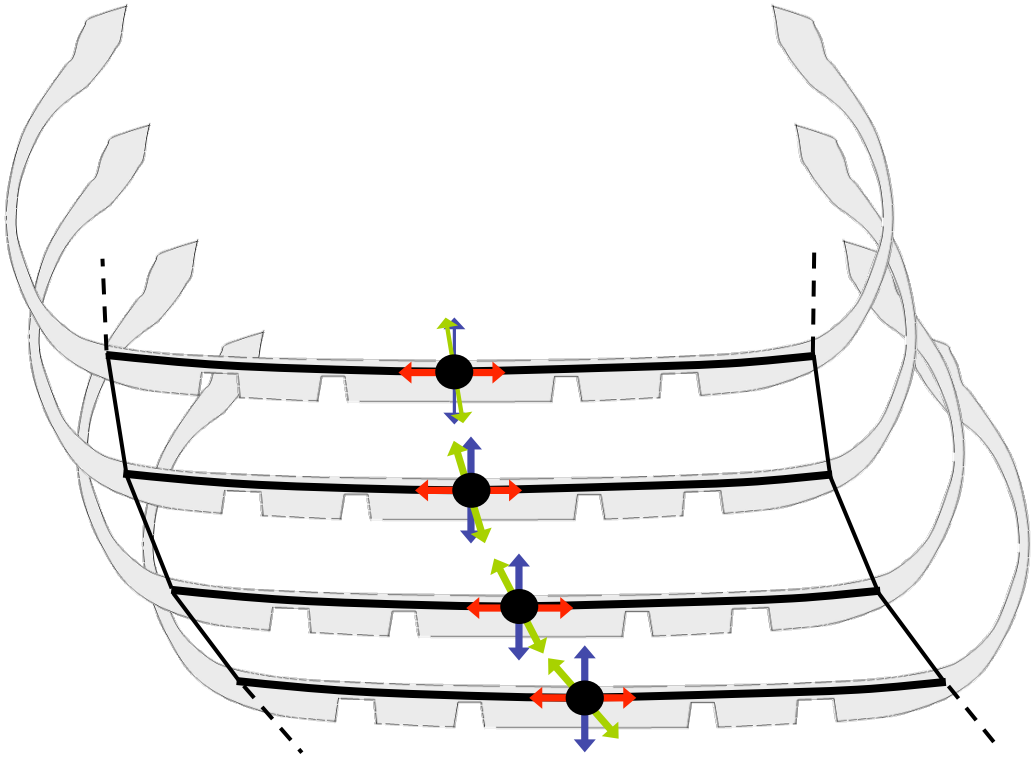
modeled by 1000..10000 (or even more) contact / friction elements connected to belt segments, sticking / sliding on road surface

Each belt segment has 4+*x* degrees of freedom:

1: longitudinal displacement

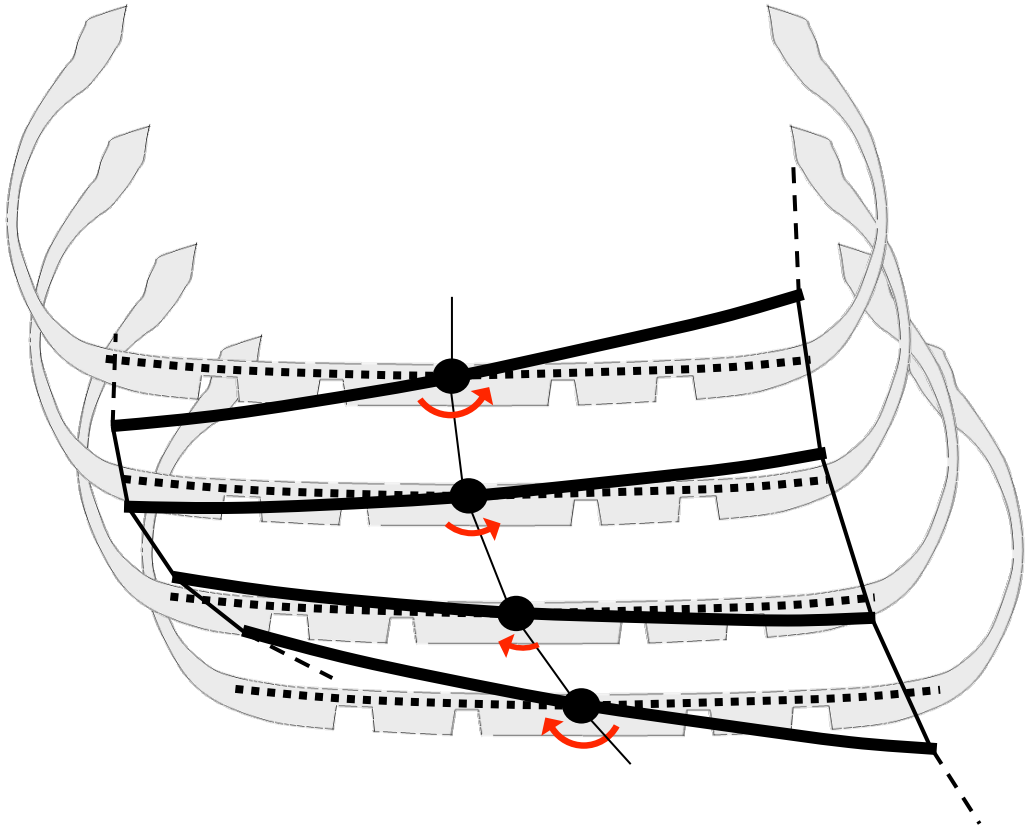
2: lateral displacement

3: vertical displacement



Each belt segment has 4+*x* degrees of freedom:

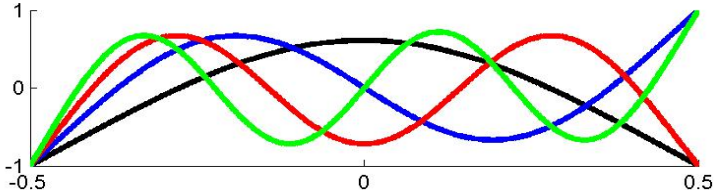
4: **rotation** about circumferential axis

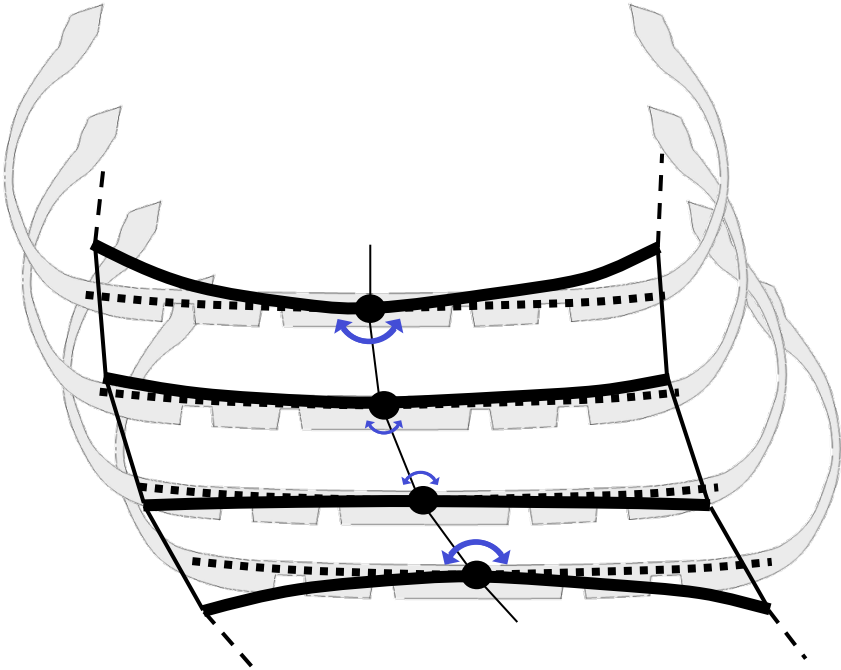


Each belt segment has 4+*x* degrees of freedom:

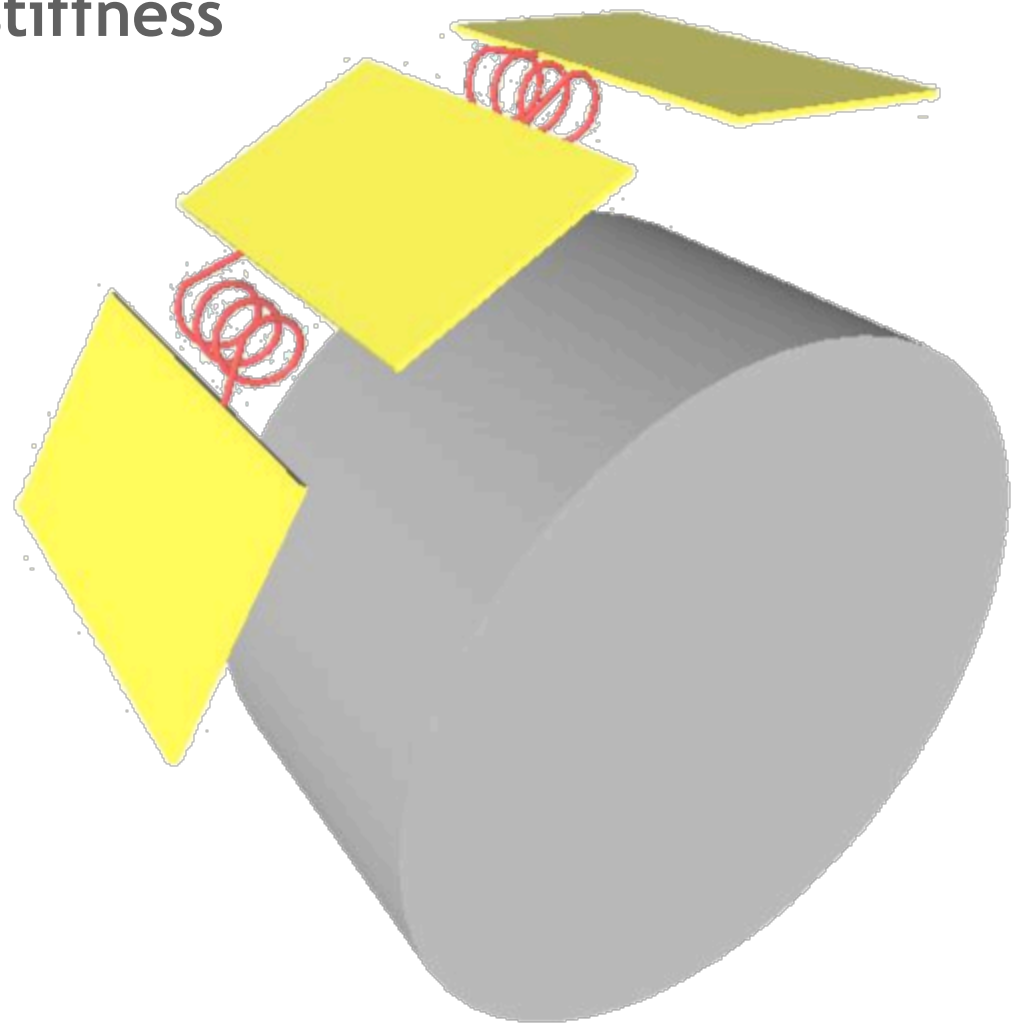
4+1 .. 4+*x*: bending in lateral direction, described by *x* shape functions

x shape functions: orthogonal bending beam eigensolutions

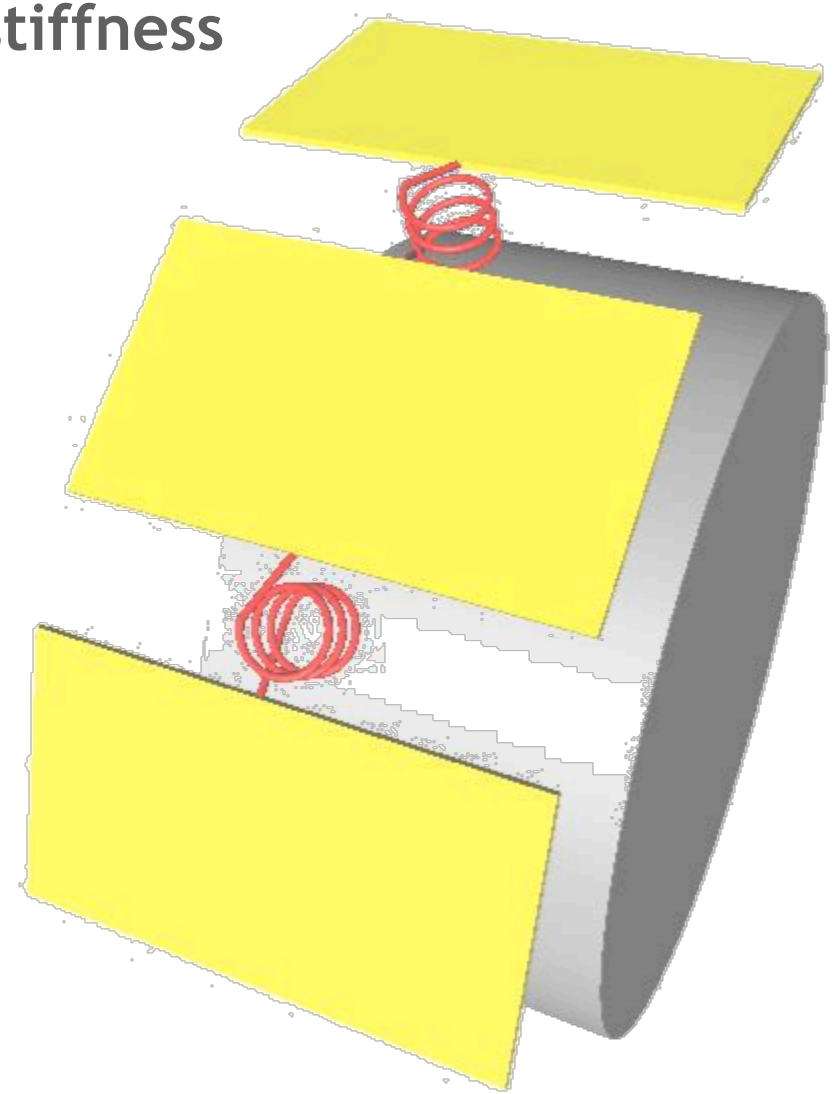




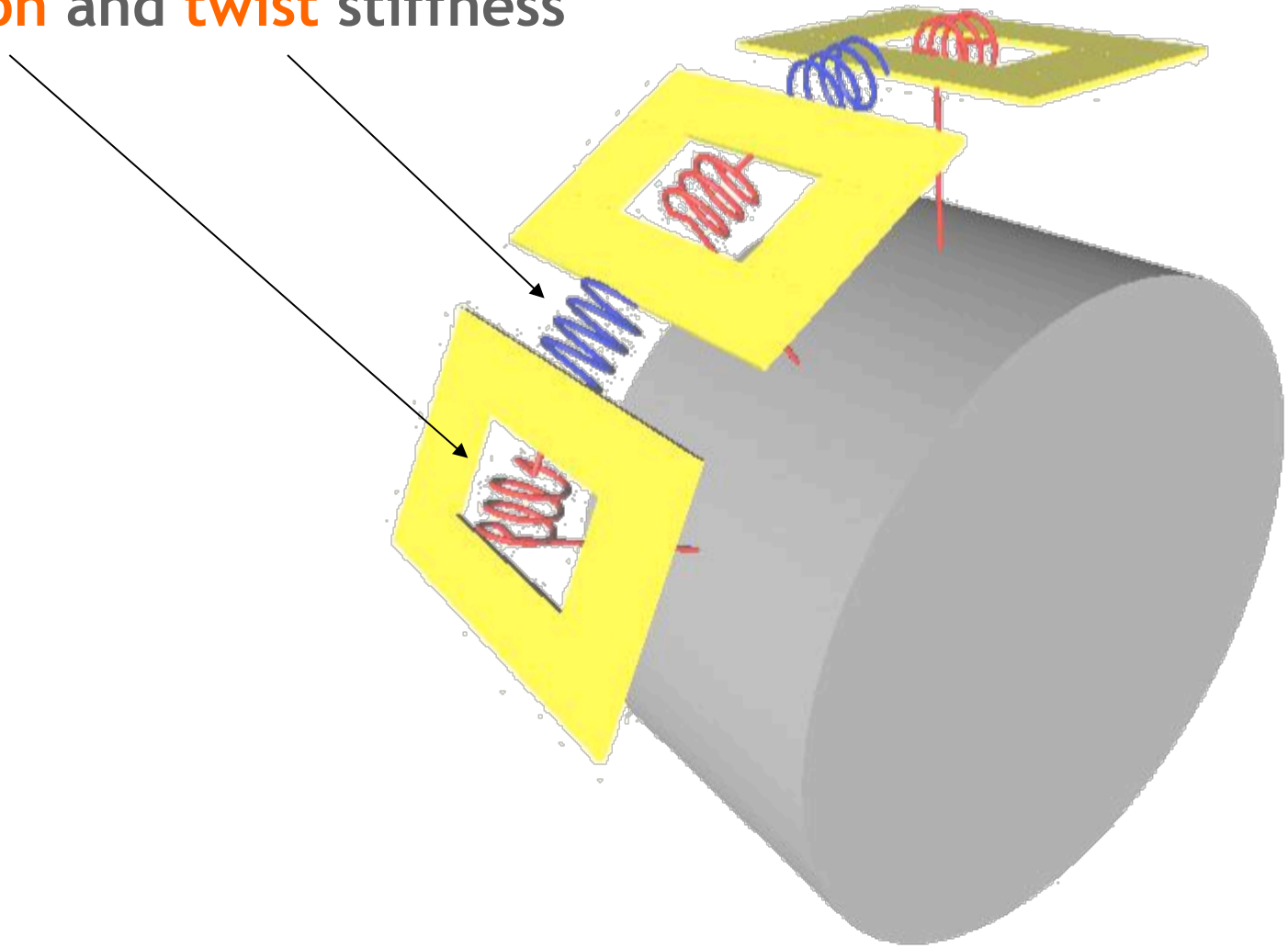
In-plane bending stiffness



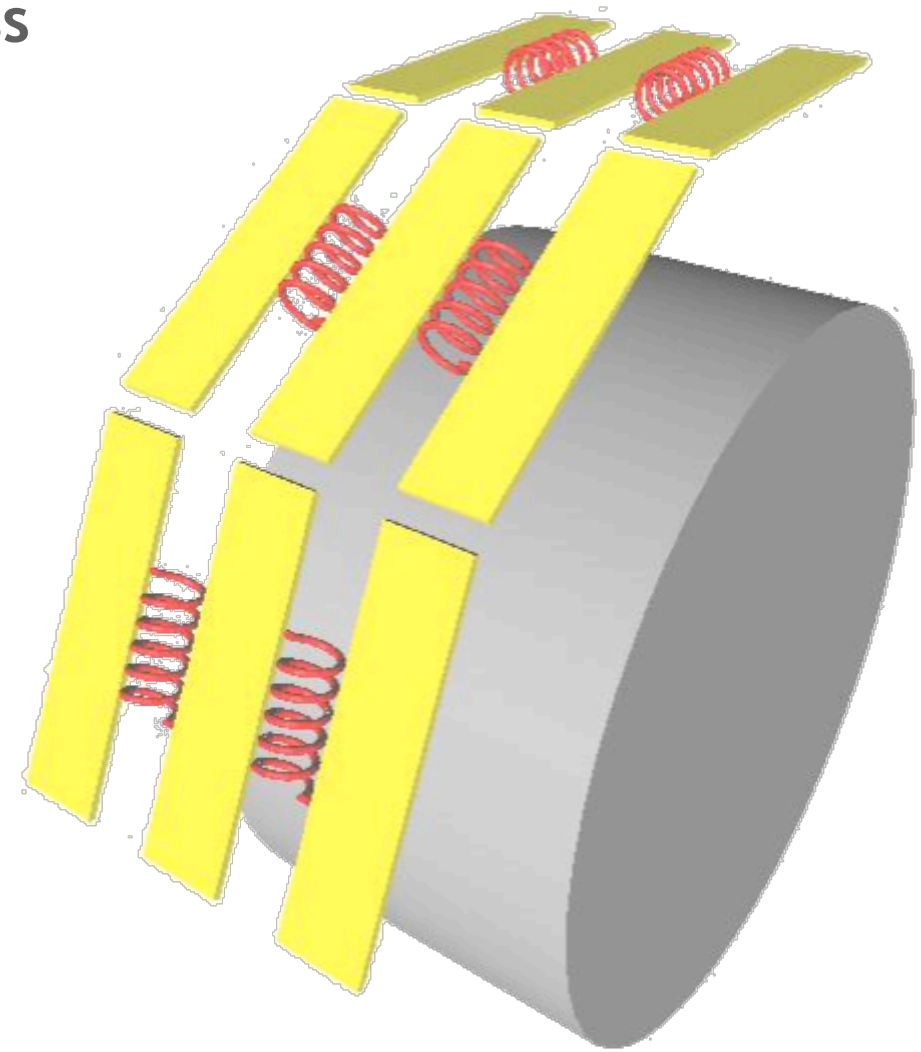
Out-of-Plane bending stiffness



Belt torsion and twist stiffness

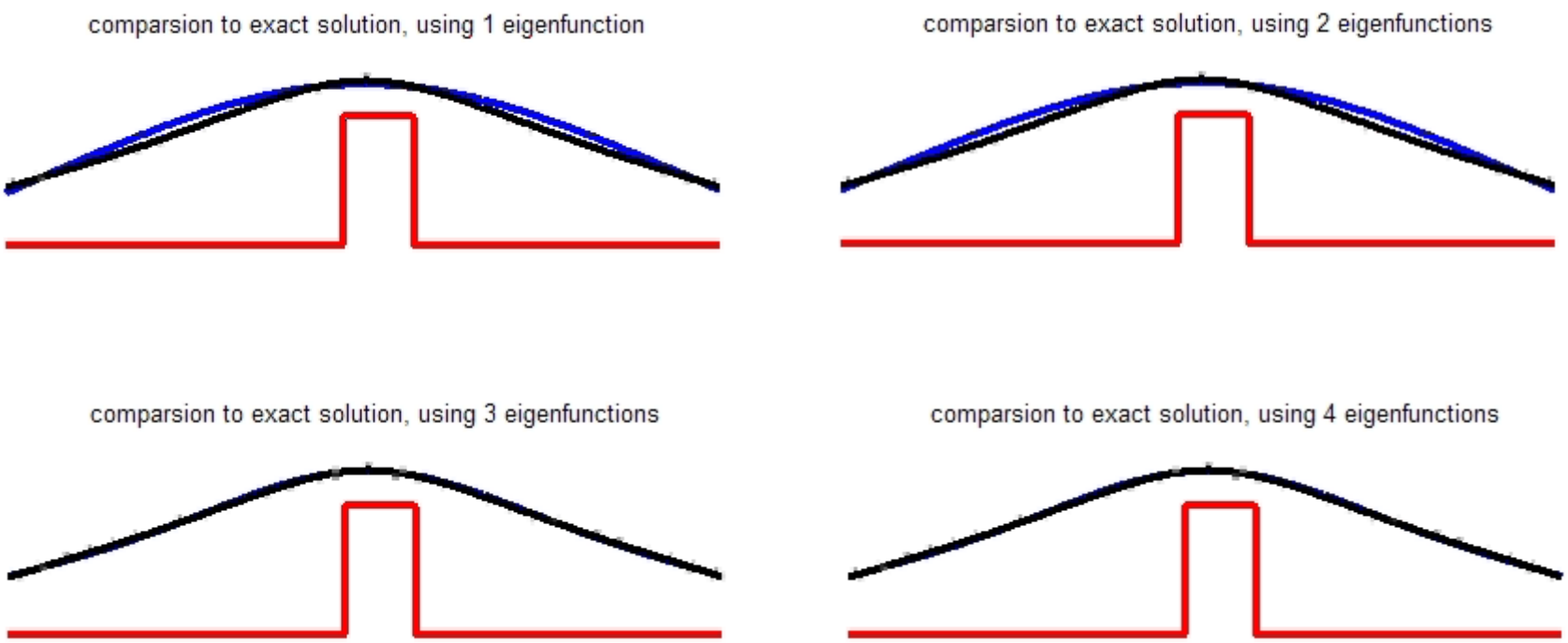


Lateral bending stiffness

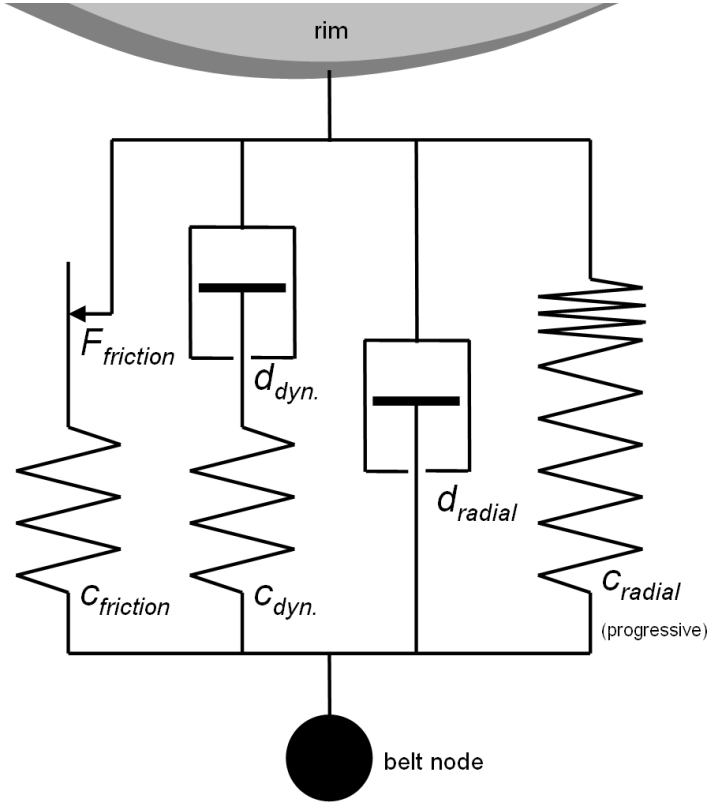


Lateral belt bending approximation

Ritz-Galerkin approach vs. **exact solution:**

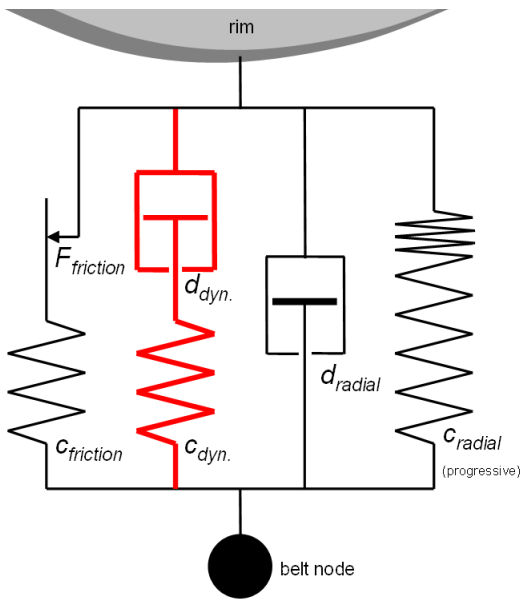


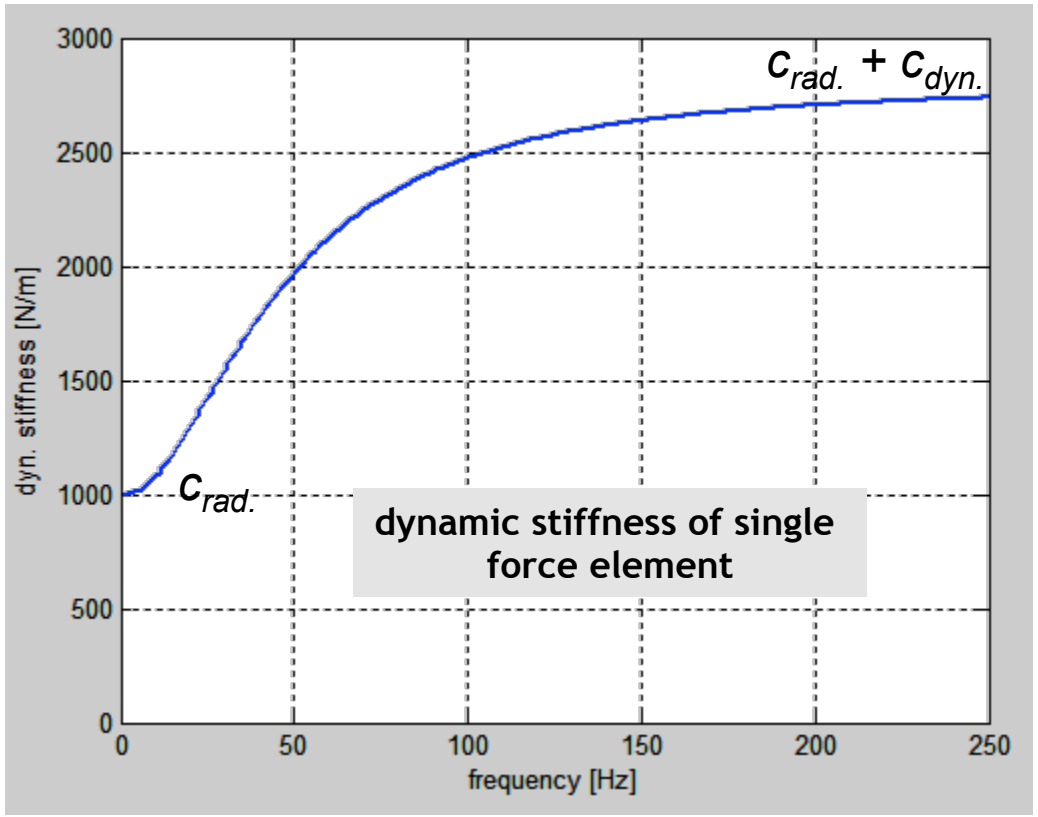
Radial stiffness of single belt segment



Dynamic radial stiffness: Maxwell elements

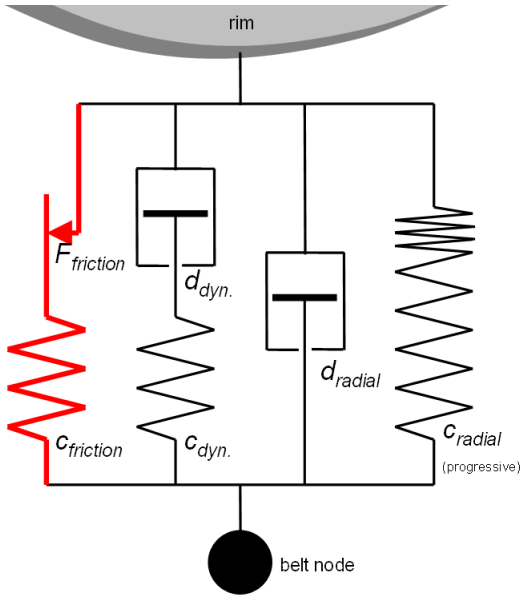
for dynamic tire stiffening at higher rolling speeds

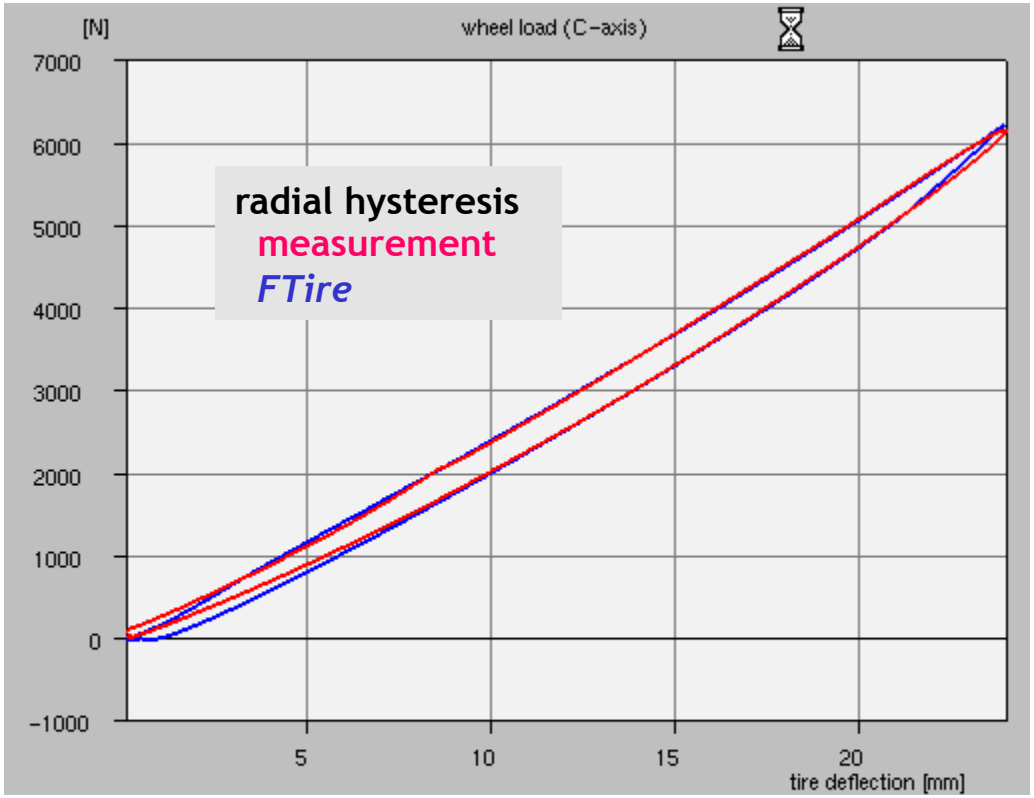




Friction element

for radial (and tangential) hysteresis modeling





Operating conditions

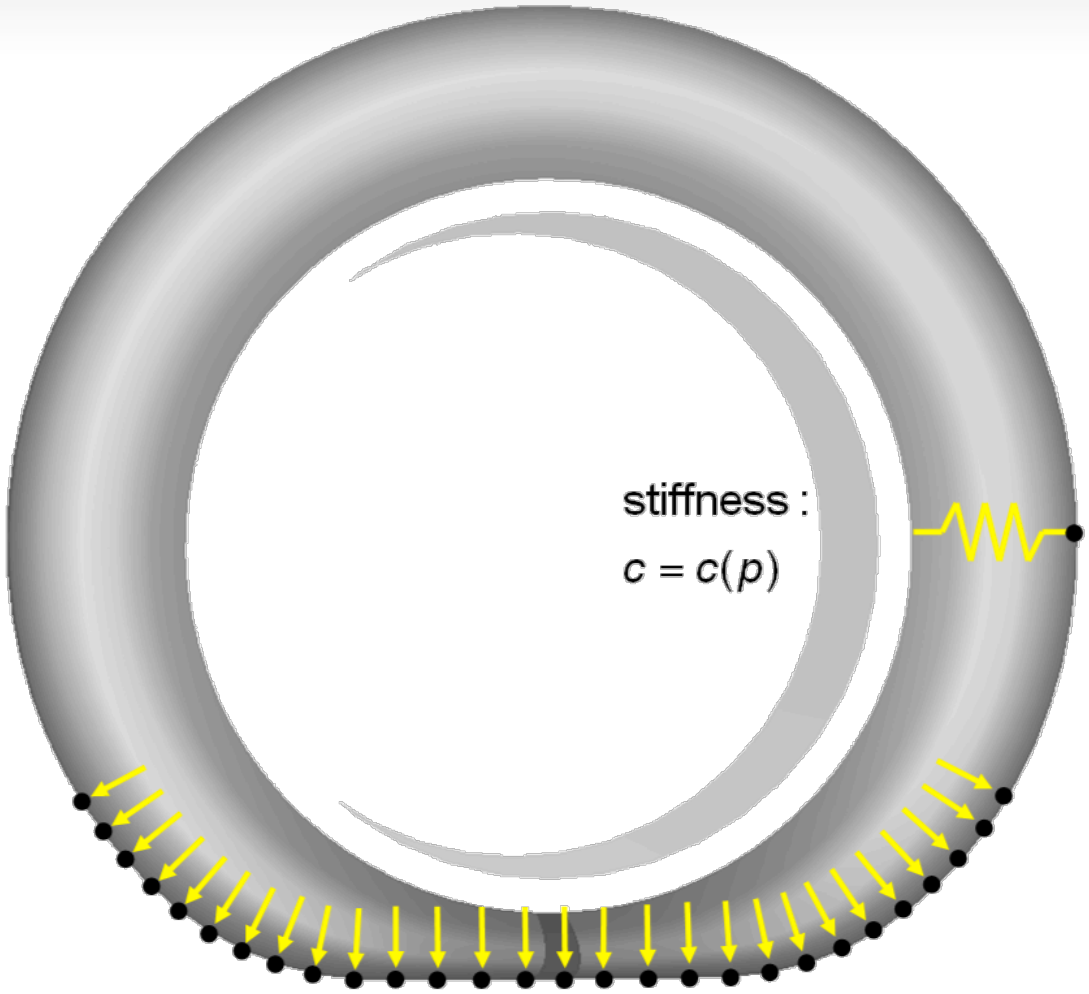
might be set or changed arbitrarily during a running simulation

- ➔ cold inflation pressure
  (actual pressure depends on temperature and more)
- ➔ tread depth
  (if not controlled by wear model)
- ➔ environmental temperature
- ➔ tire temperature
  (if not controlled by thermal model)

Inflation pressure influence

- inflation pressure is an operating condition and might arbitrarily vary during a running simulation, without any slow-down of the simulation
- pressure forces are applied to belt segments in radial direction
- every translational, rotational, and bending stiffness value depends on inflation pressure
- sudden pressure loss, up to run-on-flat simulation is possible

FTire
Inflation Pressure (2)

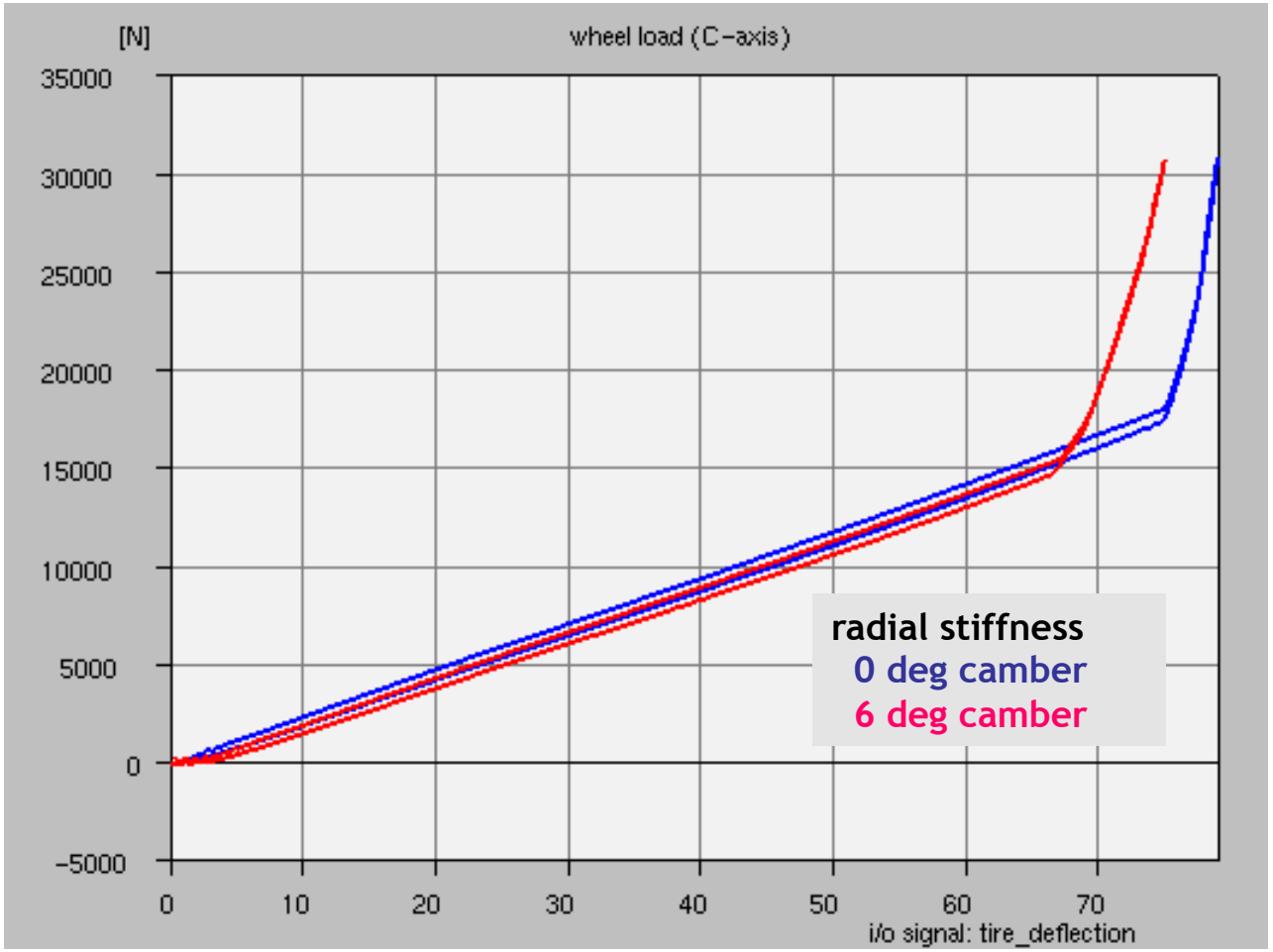


pressure forces :

$$\boldsymbol{F}_{pressure} = F(p) \cdot \boldsymbol{n}$$

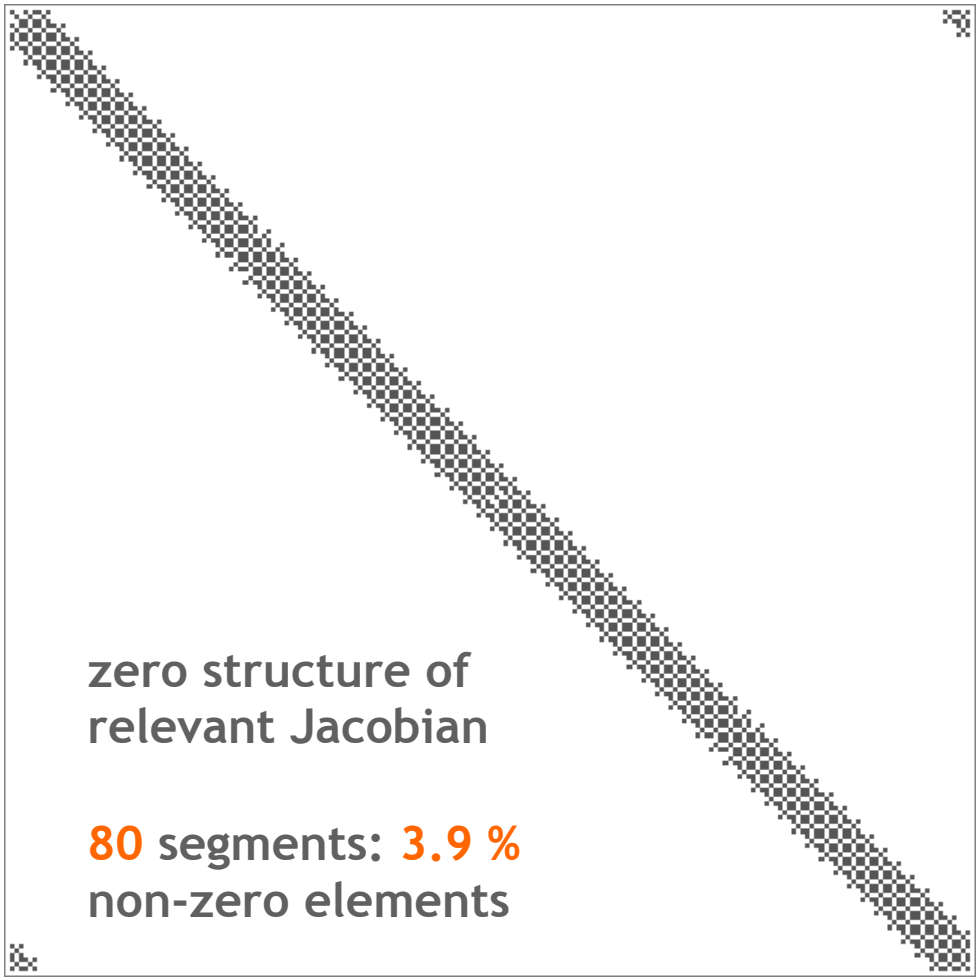
Rim-to-belt contact during misuse events

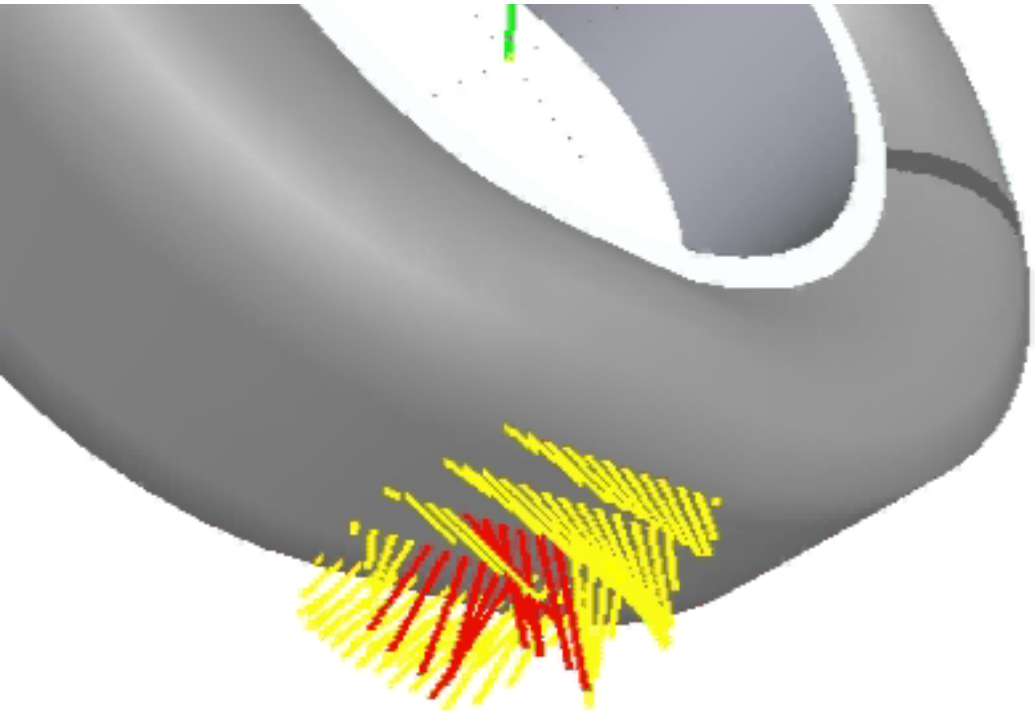
additional stiff unilateral springs, distributed along rim flanges, between rim and belt inner side



Implicit Newmark integration of structure motion

exploiting
symmetry and
sparsity properties

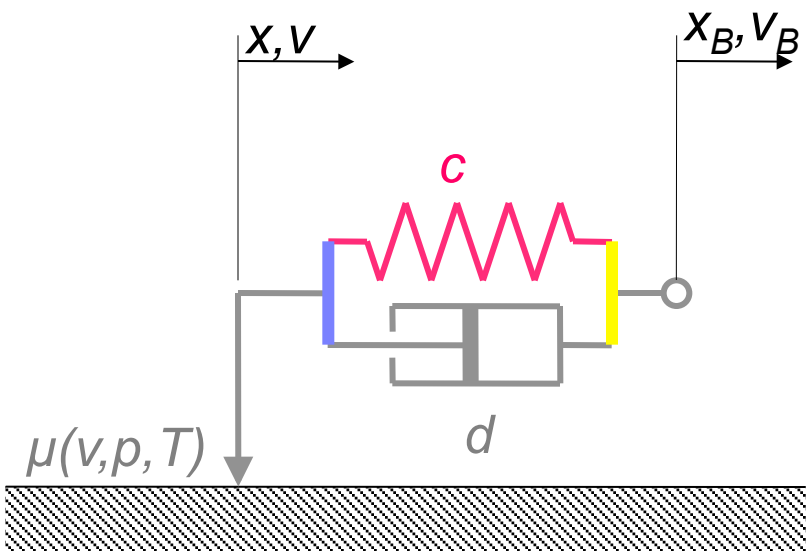




Road contact

20..100 (or more) mass-less contact/friction elements
= tread blocks
for each belt segment

use of local road tangent plane, individually for each element



force equilibrium:

$$sign(v) \cdot F_f(v) + d \cdot \left(v - v_B\right) + c \cdot \left(x - x_B\right) = 0$$

friction law:

$$F_f(v) = \mu(v,p,T) \cdot F_z$$

- ➔ full **3D motion** of tread block tip in or above road surface
- ➔ **sticking / sliding** state kept in discrete state variable
- ➔ contact plane may **move spatially** (drum, hydro-pulse, etc.)

$$sign(v) \cdot F_f(v) + d \cdot v = d \cdot v_B + c \cdot x_B - c \cdot x$$

BDF = Backward Differentiation Formula:

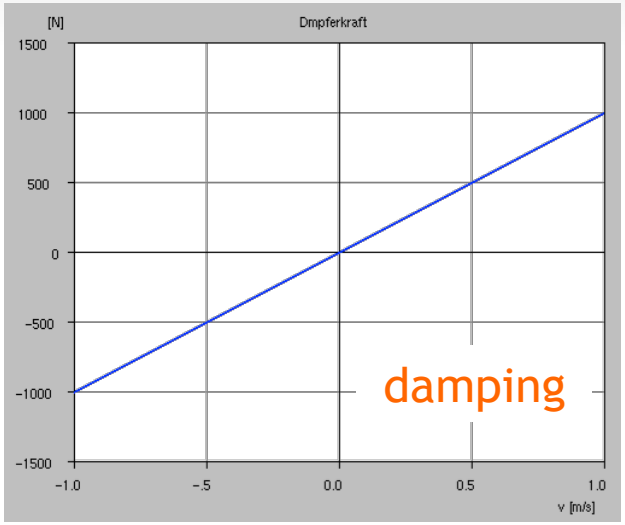
$$v = \dot{x} \approx \frac{x - x_{old}}{\Delta t}$$

$$\underbrace{sign(v) \cdot F_f(v) + \left[d + c \cdot \Delta t \right] \cdot v}_{g(v)} = \underbrace{d \cdot v_B + c \cdot x_B - c \cdot x_{old}}_{r}$$

$$g(v) = r$$

$$x = x_{old} + v \cdot \Delta t$$

FTire
Road Contact Equations (3)



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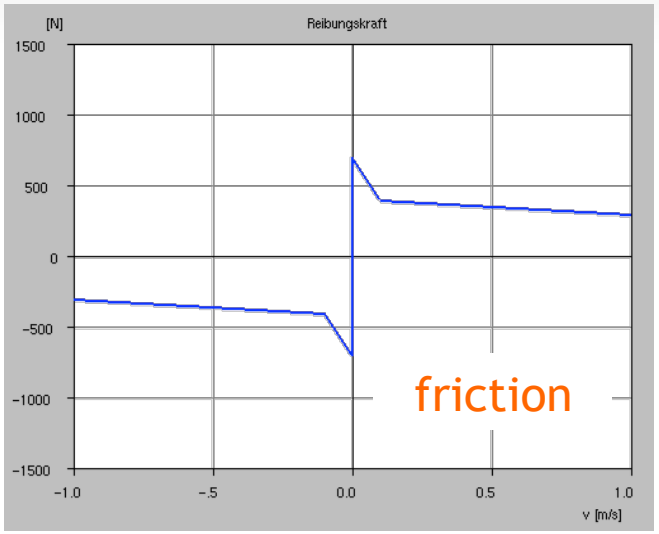

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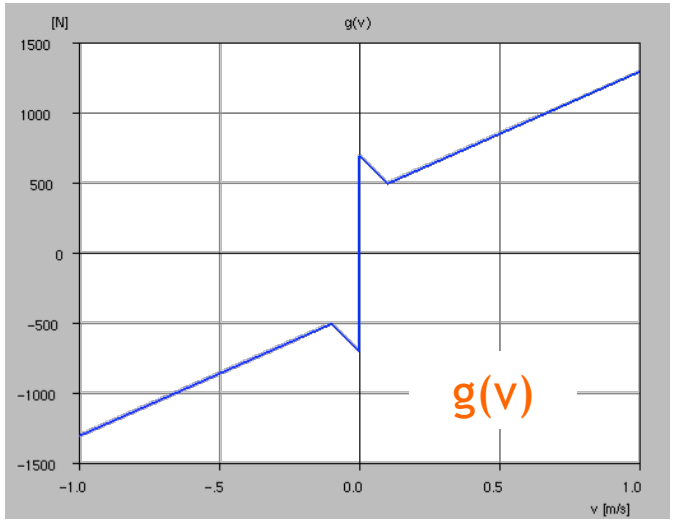
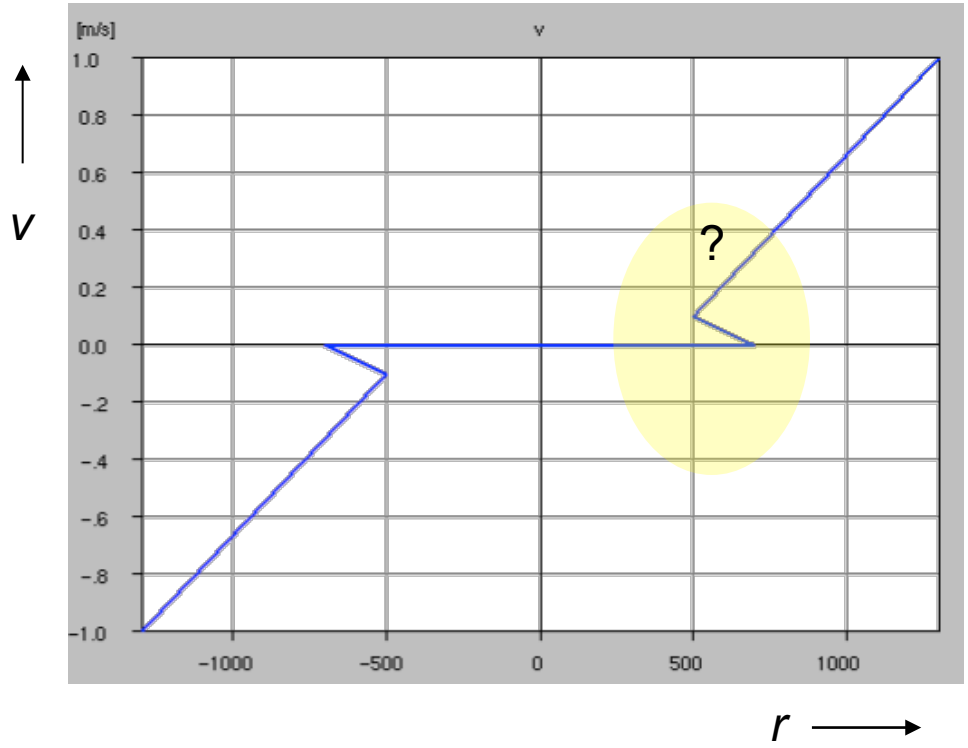
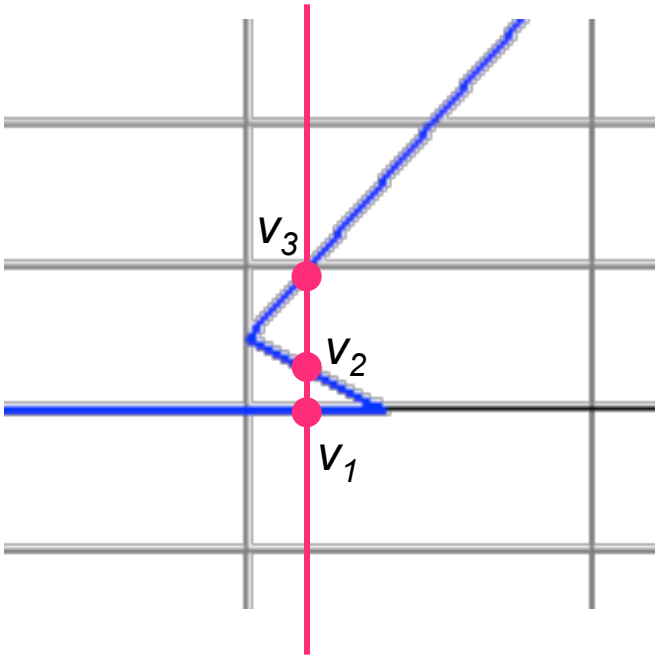


$$r = d \cdot v_B + c \cdot x_B - c \cdot x_{alt}$$

$$g(v) = r \quad \Rightarrow \quad v = g_{invers}(r)$$



$$x = x_{old} + v \cdot \Delta t$$



choose v_1, if state is ‚sticking‘

choose v_3, if state is ‚sliding‘

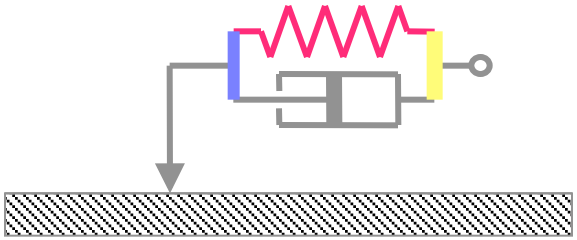
change state to ‚**sticking**‘, if $|v| < \varepsilon$

change state to ‚**sliding**‘, if $|v| \geq \varepsilon$

- ➔ sticking/sliding is a discrete **state variable**
- ➔ friction elements are **discontinuous**, but even though numerically stable

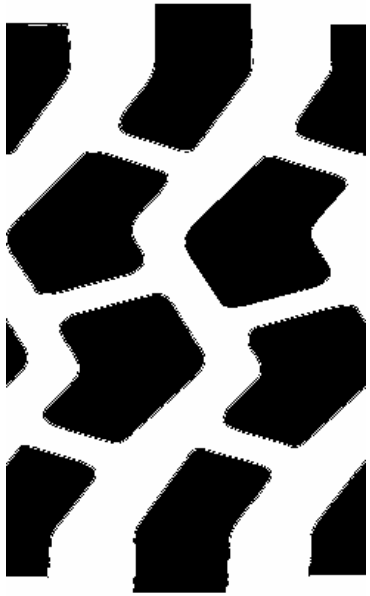
Validation program of single friction element dynamics

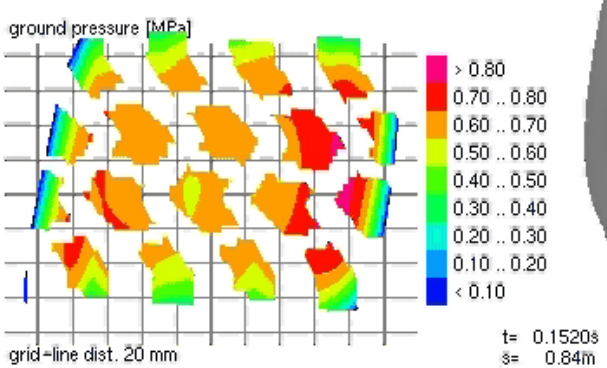
(optionally with mass)



Tread pattern description by b/w or greyscale bitmap file

for simple patterns

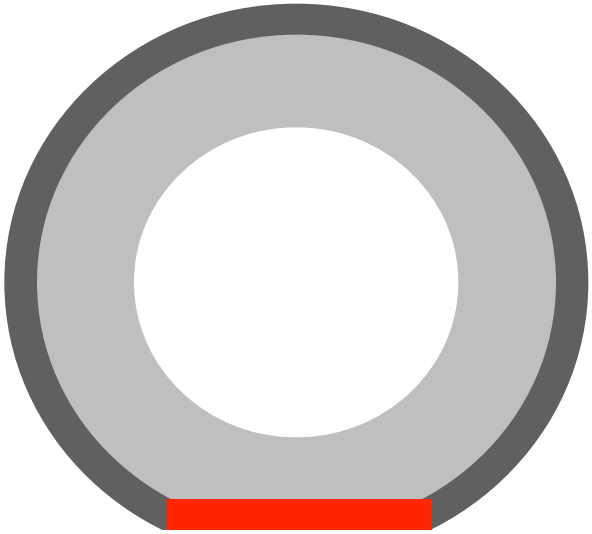




Thermal model

- ➔ tire structure temperature influences **inflation pressure** via $pV = kT$ (and thus indirectly the tire stiffness)

- ➔ distributed tread temperature influences **road friction characteristic**



Regions with different thermal properties:

- tire structure (side-wall, belt, air volume)
- tread outside contact patch
- contact patch (**distributed** temperature)

Thermal model

- heating due to structural damping and friction in contact patch
- cooling by convection and radiation in sidewall and tread (depending on rolling speed and ambient temperature)
- heat transfer between regions determined by heat transfer coefficients

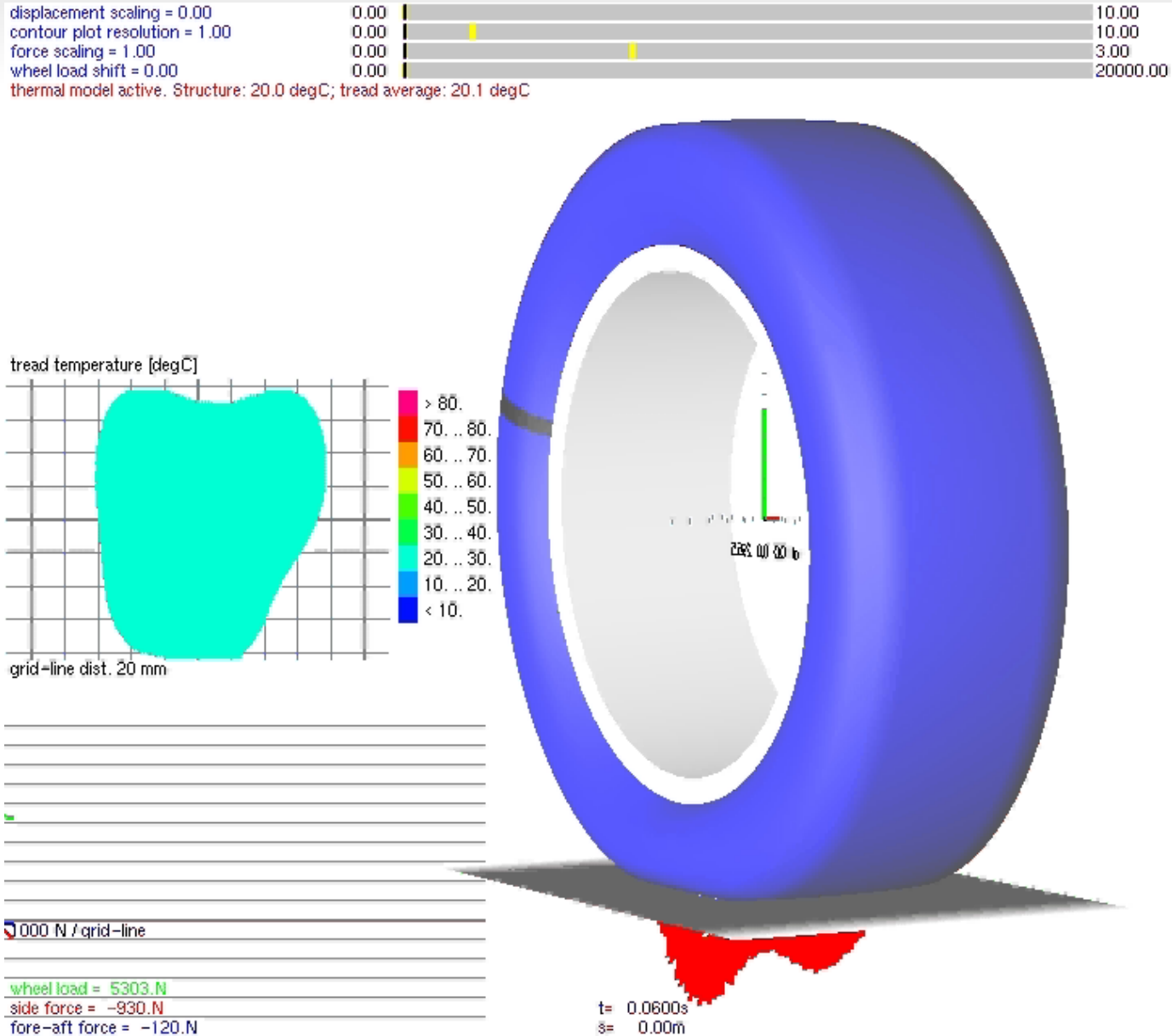
heat transfer coefficients and heat capacities

determined by

steady-state temperatures and heating time constants

FTire

Thermal Model: Temperature During Side-Slip Sweep



side-slip angle
±10 deg
camber angle
2 deg

Tread wear model

For each individual tread block, wear rate is assumed to be a function of friction power and temperature:

$$\dot{h}_{tread} = -f_{wear}\left(P_{loss} , T_{tread} \right)$$

where

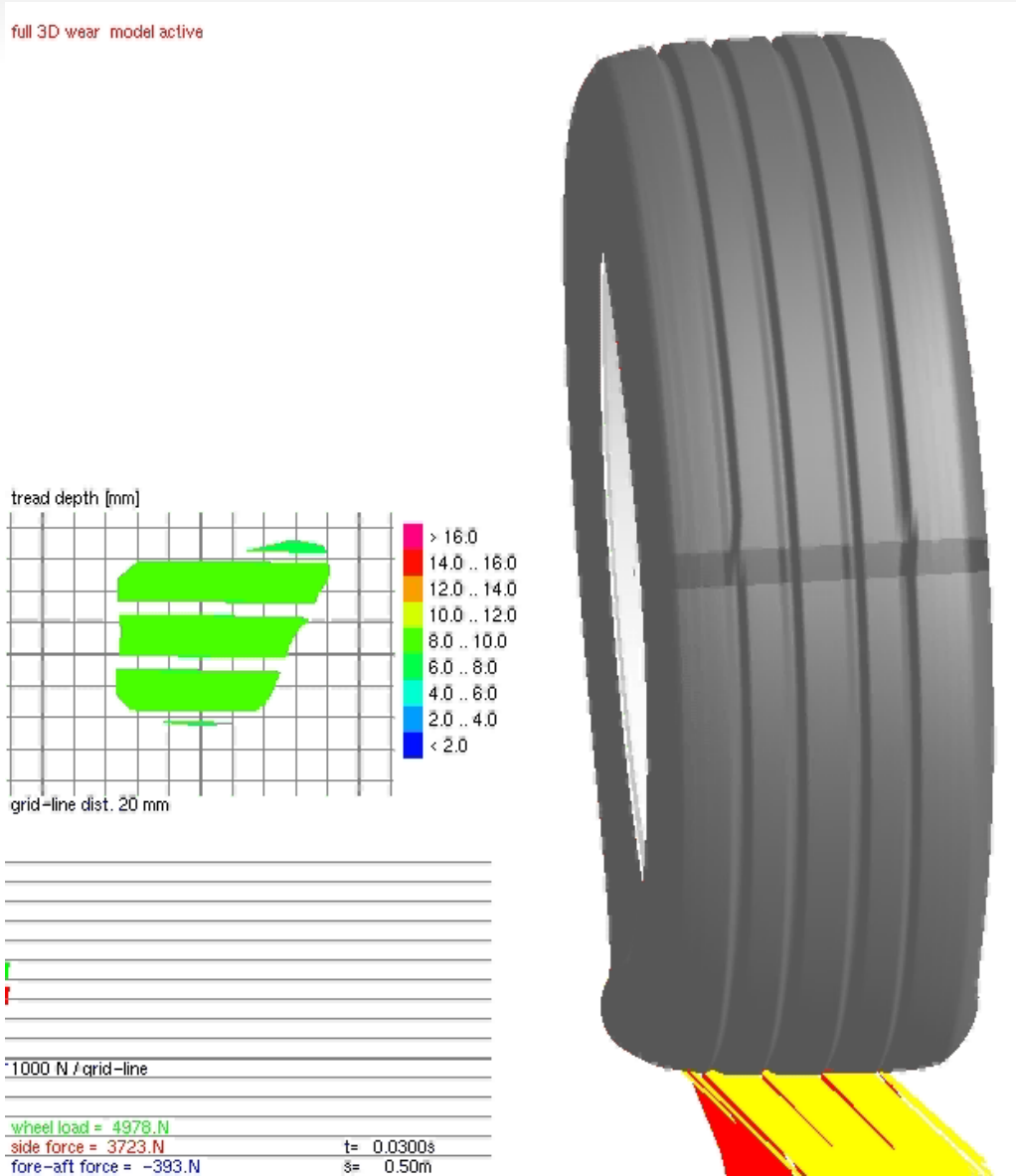
$$P_{loss} = \left| F_f \right| \cdot \left| v_{slide} \right|$$

each tread block's height is treated as an additional state variable

Tread wear model

Change in tread depth affects

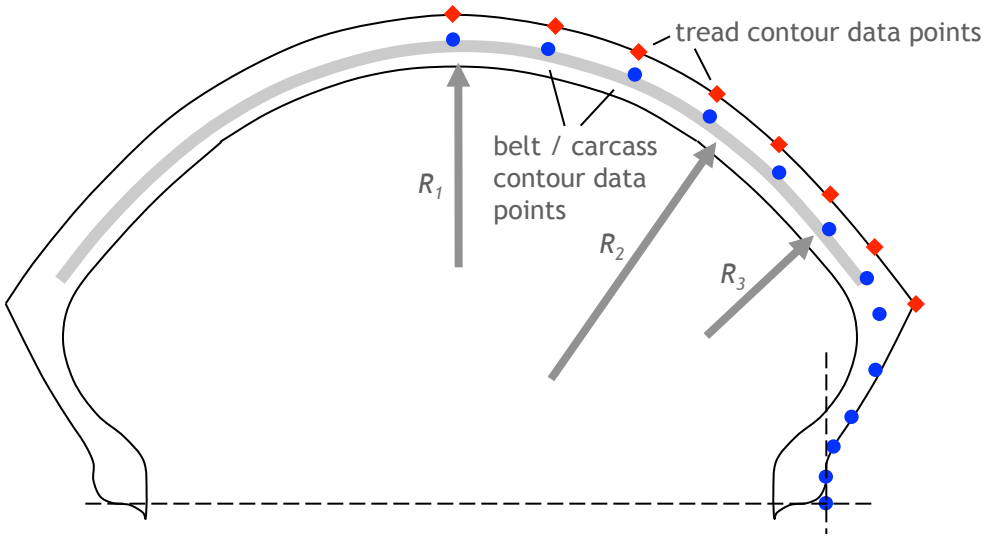
- ➔ tread **geometry**
  (and thus ground pressure distribution)
- ➔ **compression stiffness** and damping
- ➔ **shear stiffness** and damping
- ➔ **mass**
- ➔ **heat capacity**



FTire improvements for motorcycle tires:

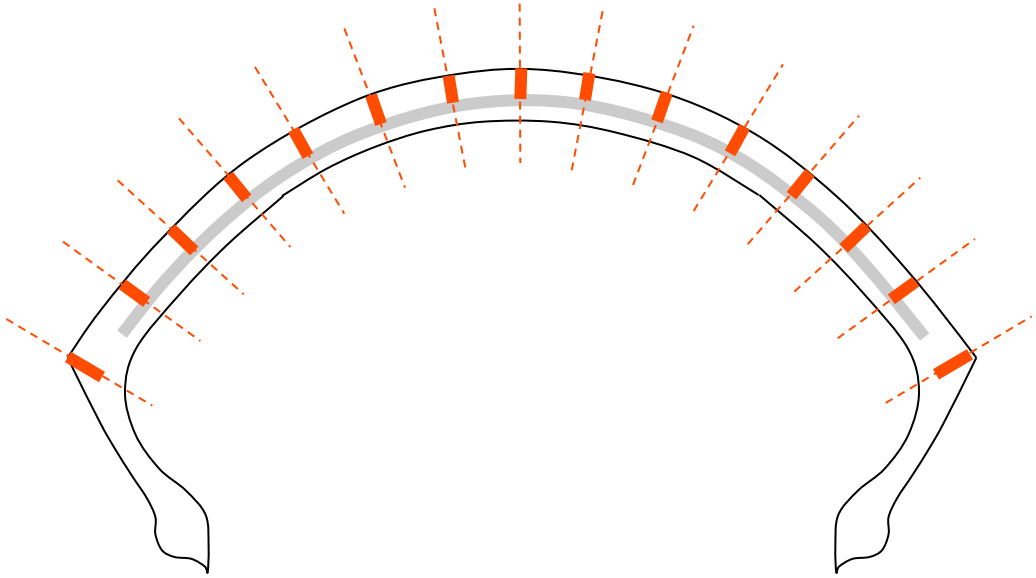
FTire improvements for motorcycle tires:

➔ detailed, spline-data based **cross-section geometry**



FTire improvements for motorcycle tires:

- detailed, spline-data based cross-section geometry
- contact elements oriented along true belt normal



FTire improvements for motorcycle tires:

- detailed, spline-data based cross-section geometry
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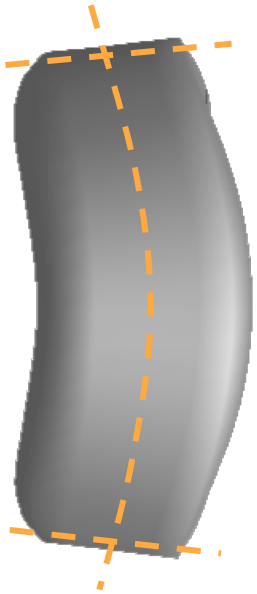
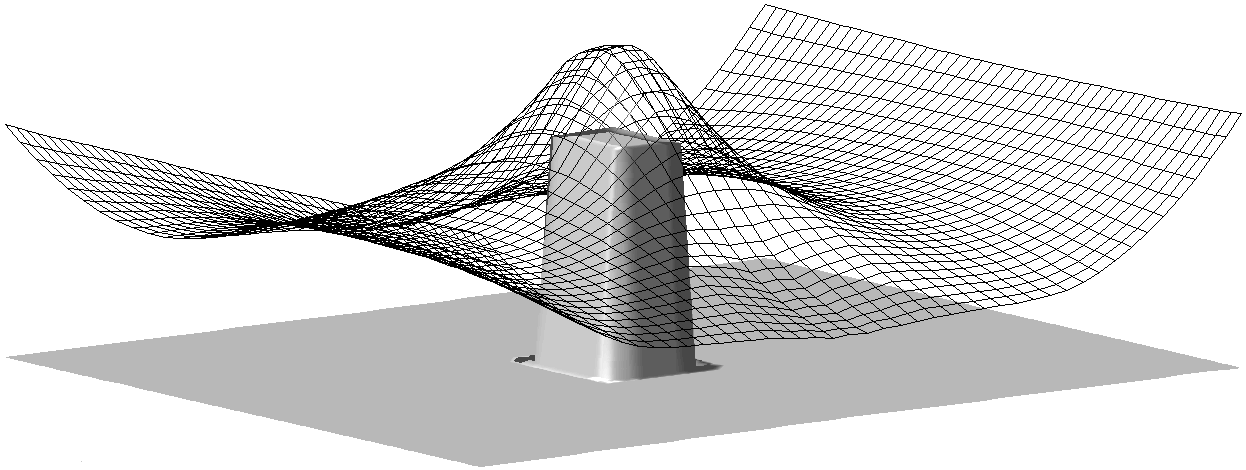
- kinematic coupling of belt torsion and out-of-plane bending



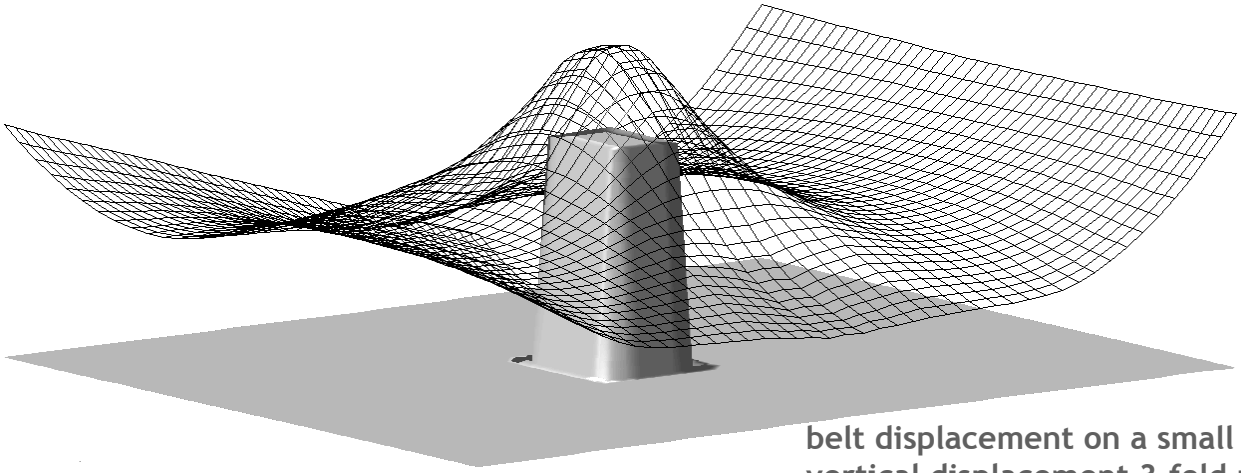
FTire improvements for motorcycle tires:

- detailed, spline-data based cross-section geometry
- contact elements oriented along true belt normal
- kinematic coupling of belt torsion and out-of-plane bending
- enhanced belt flexibility in lateral direction

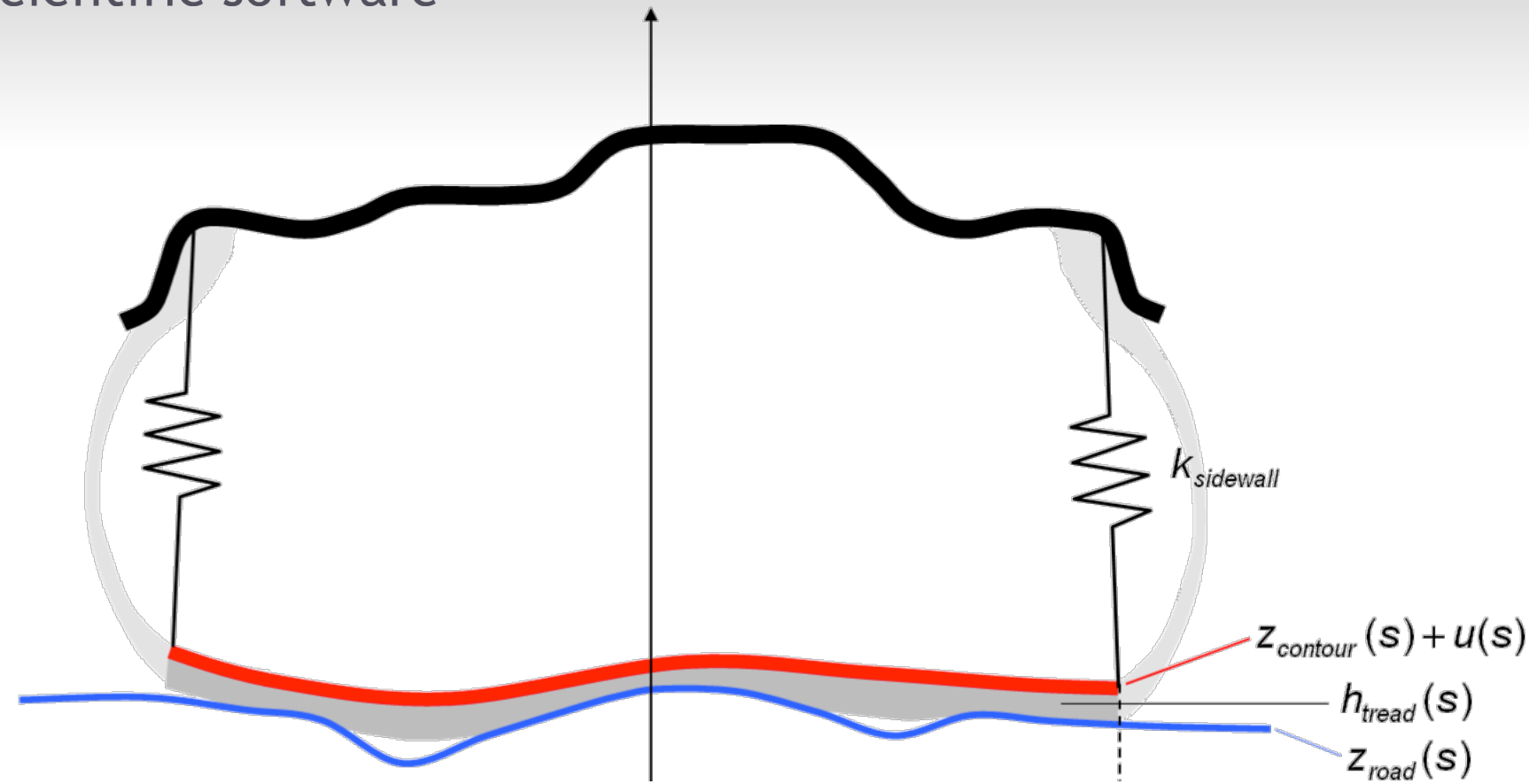


Enhanced model of belt bending in lateral direction

- lateral bending degrees of freedom for each belt segment: coefficients of bending beam eigensolutions
- longitudinal coupling with smoothing coefficient



belt displacement on a small obstacle
vertical displacement 3-fold magnified



beam equation $EI \cdot u^{(IV)} = f_{cont}$ + appropriate boundary conditions

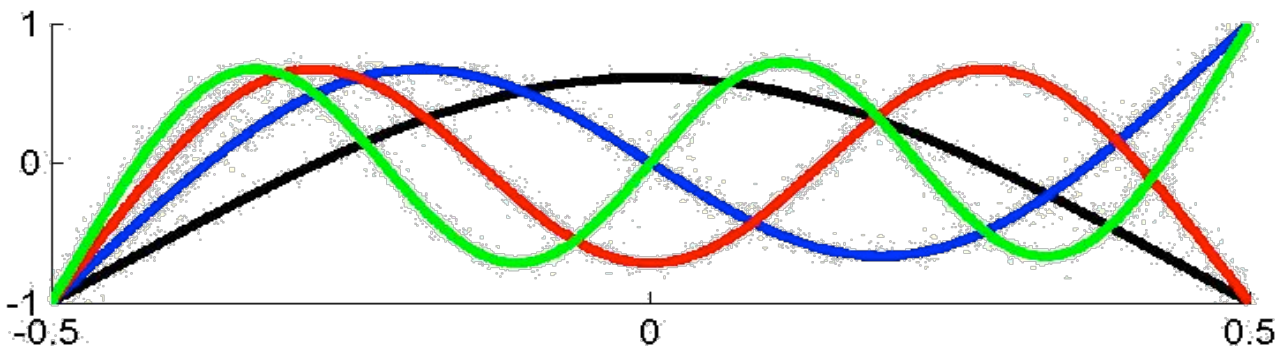
unilateral contact force $f_{cont}(s) = \left[k_{tread} \cdot \left(z_{road}(s) - z_{contour}(s) - u(s) + h_{tread}(s) \right) \right]^{+}$

lateral belt bending **trial function**

$$u^{approx}(s) = \alpha + \beta \cdot s + \sum_{i=1}^{N} \gamma_i \cdot q_i(s)$$

shape functions =
beam eigensolutions

$$EI \cdot q_i^{(IV)} = \lambda_i q_i$$



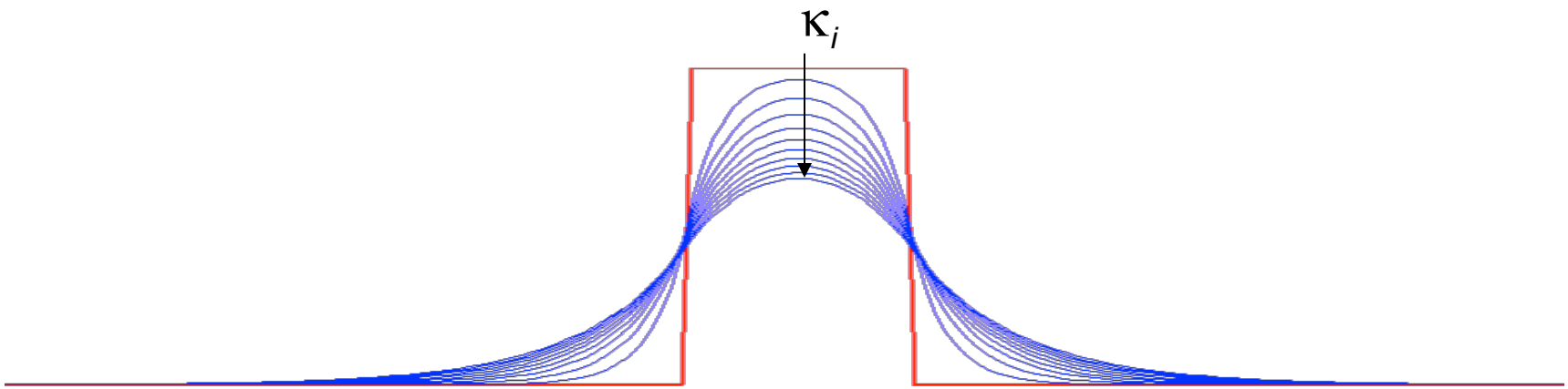
simple computation of
coefficients in segment *k*
due to **orthogonality**

$$\gamma_i^k = \frac{1}{EI} \int_{-0.5w}^{0.5w} f_{cont}^k(s) \cdot q_i(s) ds = \frac{1}{EI} f_i^k$$

smoothing in longitudinal direction

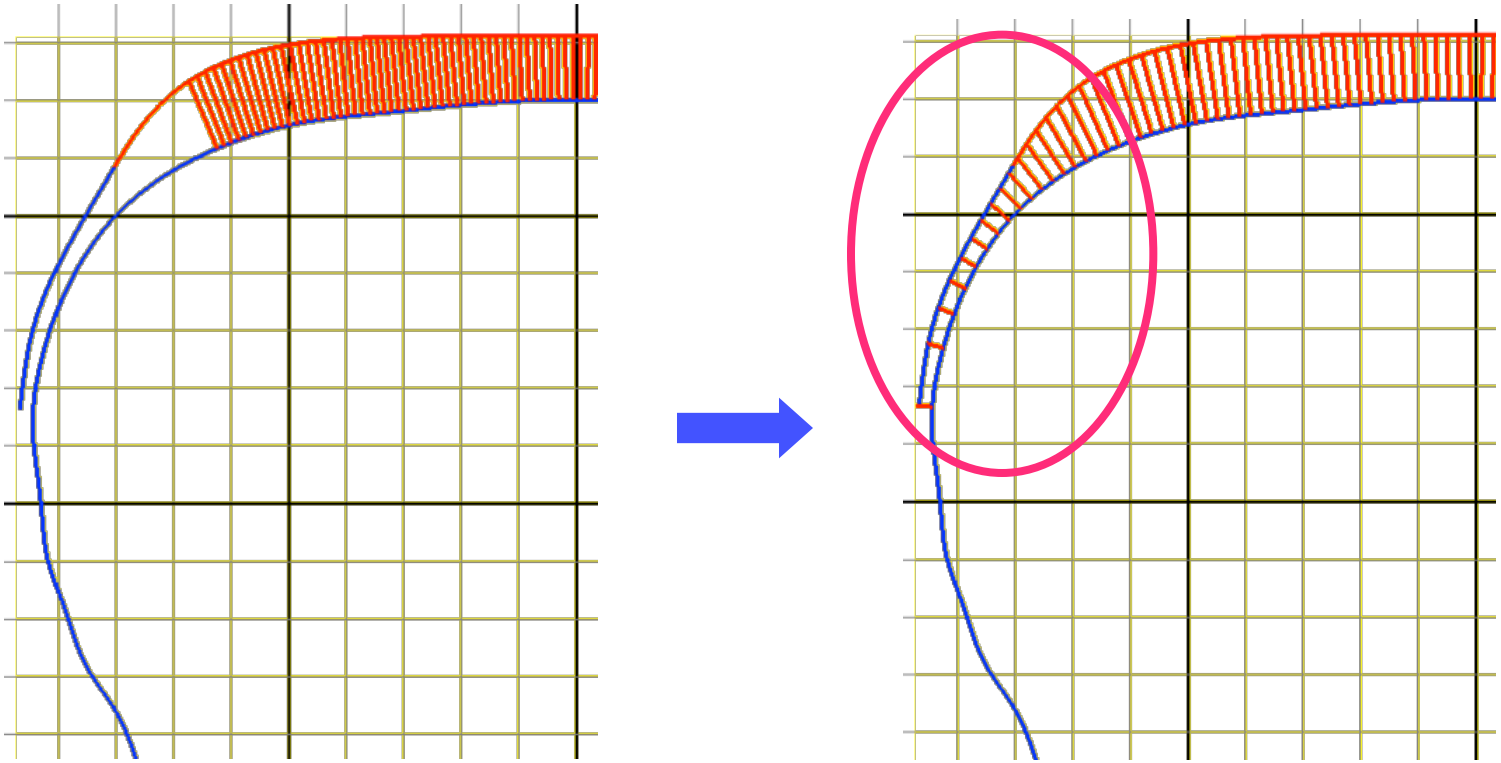
by additional
coupling term between
adjacent segments

$$\gamma_i^k + \kappa_i \cdot \left(-\gamma_i^{k-1} + 2\gamma_i^k - \gamma_i^{k+1}\right) = \frac{1}{EI} f_i^k$$



Side Wall Contact

'tread' contact elements extended over outer half of side walls

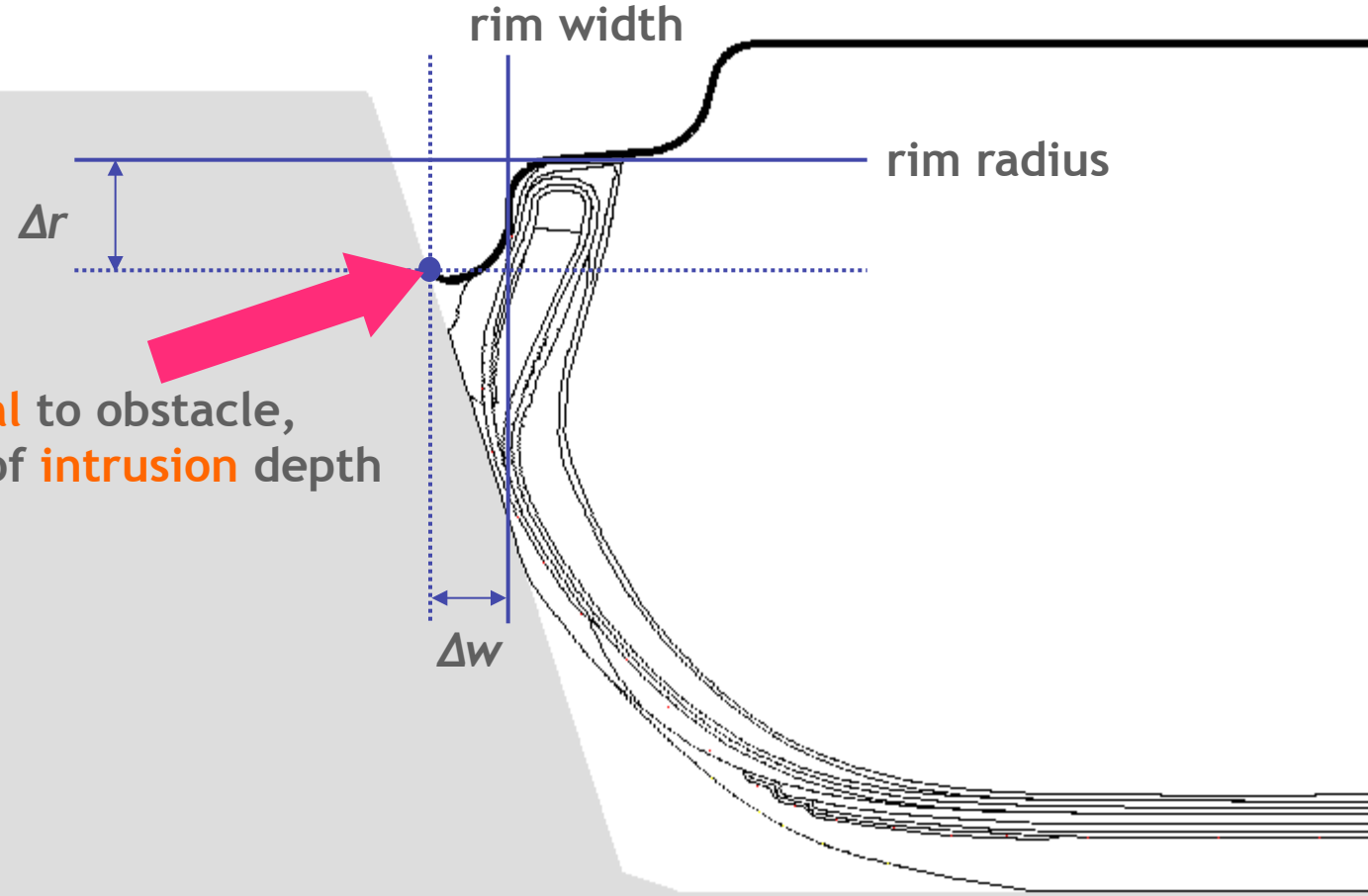


Side Wall Contact Not Activated by Default
Pros & Cons:

- ✔ indispensable for misuse simulations with lateral curb contact
- ✔ increased model fidelity at extremely large camber angles (roll-over)
- ✔ fully general friction model used

- ✘ tread resolution gets poorer in standard situations
- ✘ simplified model for lateral belt bending when side wall is in contact
- ✘ effective normal stiffness difficult to determine
- ✘ for numerical reasons, only outer half of side wall taken into account

Rim-To-Road Contact

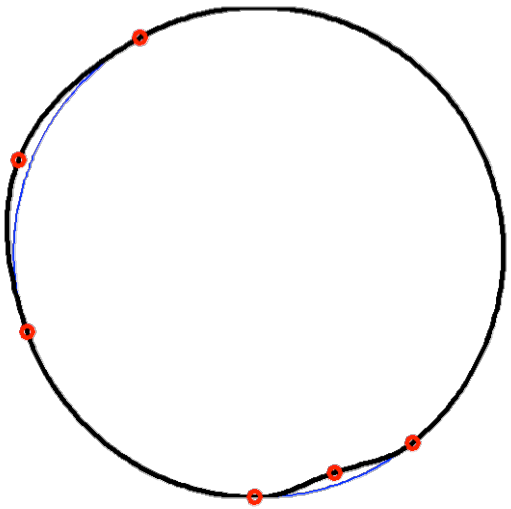


contact force normal to obstacle,
nonlinear function of intrusion depth

Imperfection Spline Data, Varying along Circumference

- Radial non-uniformity (stiffness variation)
- Tangential non-uniformity (stiffness variation)
- Radius variation
- Tread gauge variation
- Mass distribution variation

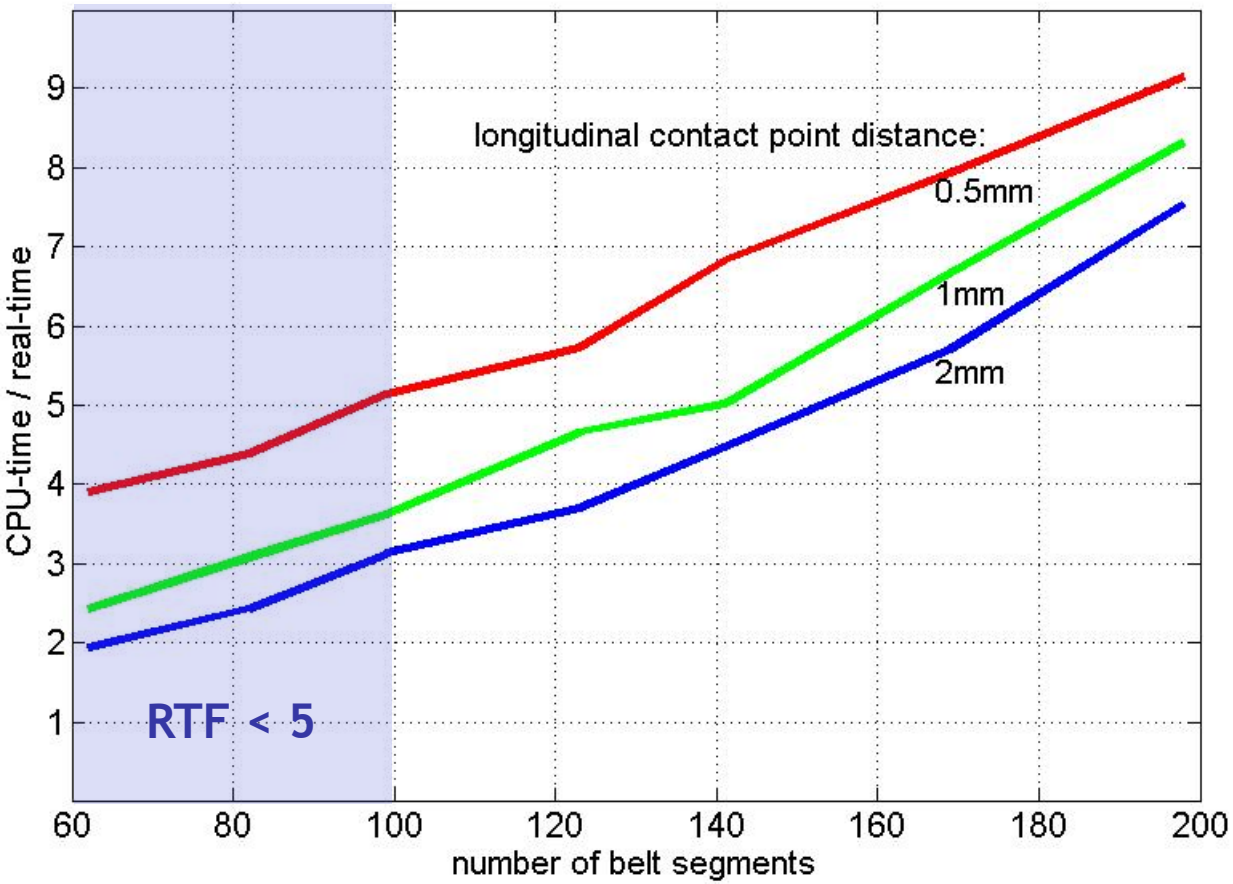
```
radius_var_vs_angle_spline =
 120    0
 160    5
 200    0
 270    0
 290   -5
 310    0          ! [deg], [%]
```



piecewise linear or smooth spline interpolation selectable

CPU time

Δt = 0.5 ms, Intel Pentium 3GHz, single thread, Windows 32bit



..thank you for your attention!

Q & A

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