Dynamic simulation of the inflation gas of a tire under operational conditions

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2nd European Multibody Simulation User Group Meeting

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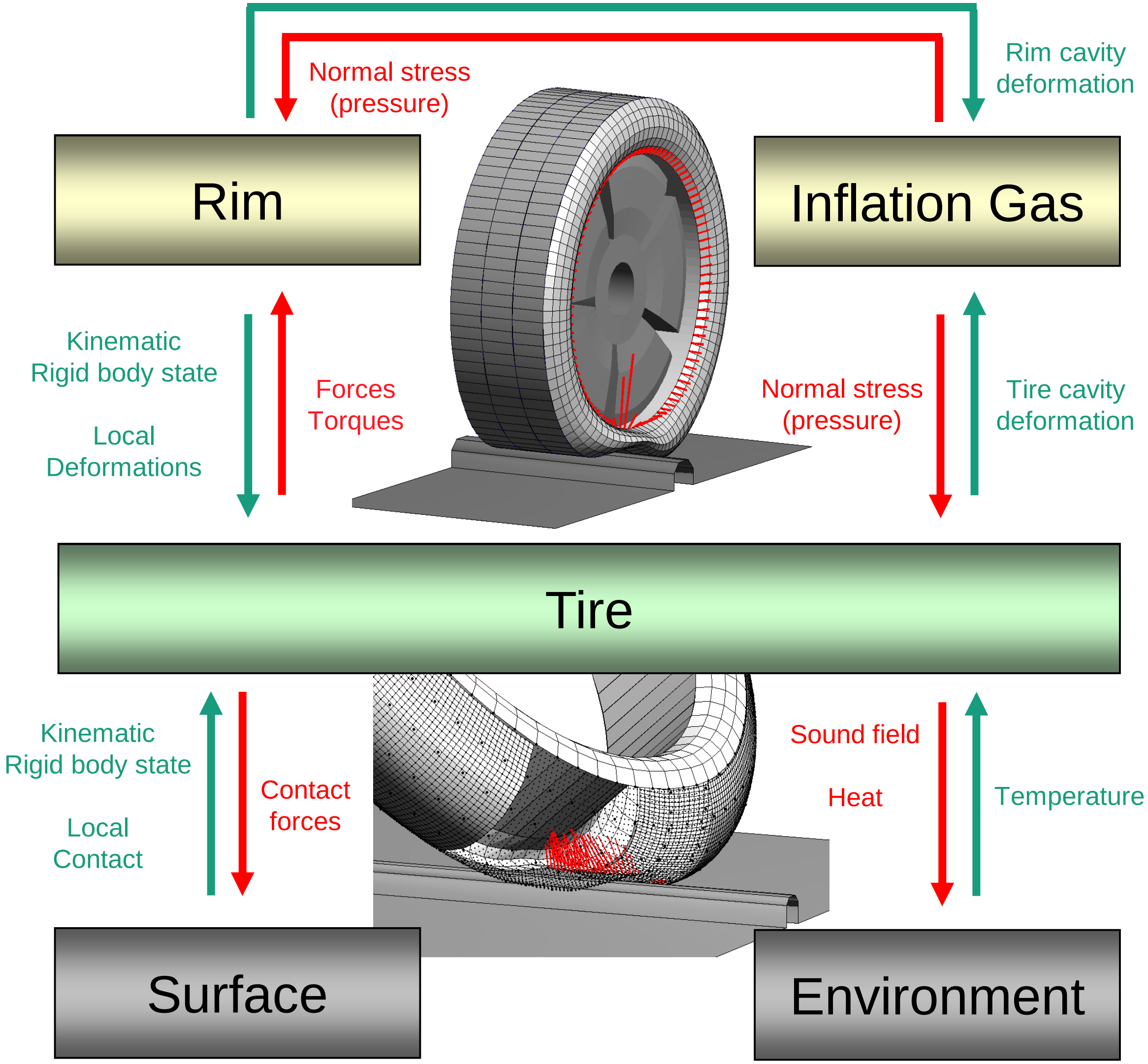
Multi-physics aspects of tire simulation

- **Mechanical model**
  - Large deformations
  - Cords, filled rubber
  - Frictional contact

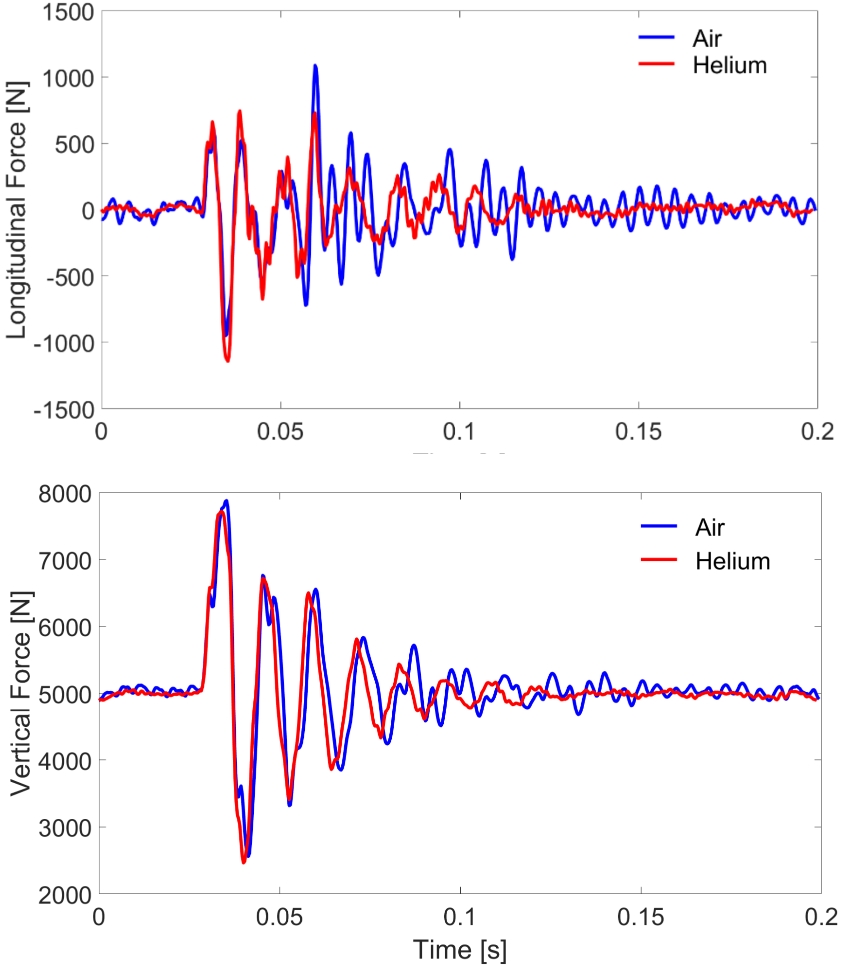
- **Temperature model**
  - Heat propagation
  - Structural effects
  - Frictional effects

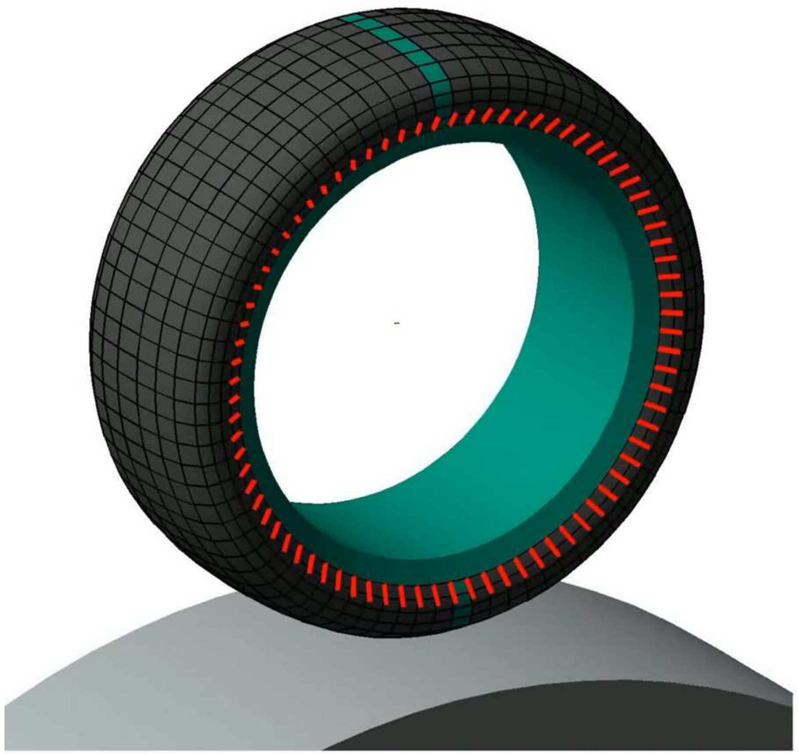
- **Cavity model**
  - Euler equation
  - Coupled with tire



Air (black) vs. Helium (red)

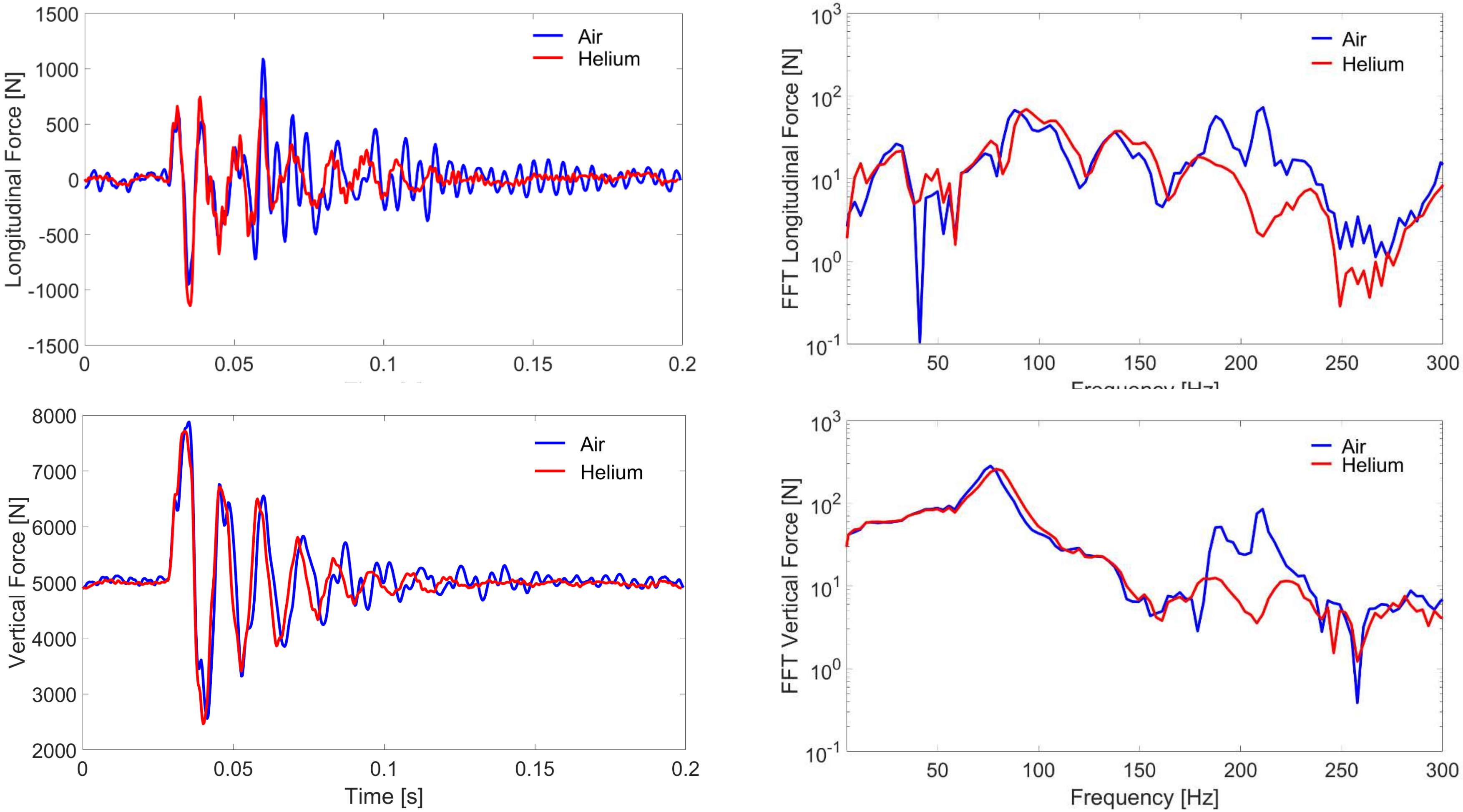
- 9 Cleat runs (3 preloads a 3 velocities), measurements courtesy fka





Motivation: Inflation Gas Air (black) vs. Helium (red)

- **Cleat run (5000 N, 90 km/h, 10x20 mm), measurements courtesy fka**



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CDTire model family

- **CDTire/3D** – detailed shell-based 3D structural model
- **CDTire/Realtime** – physical tire model for applications from comfort to durability under soft and hard realtime conditions
- **CDTire/MF++** – enhanced Magic Formula for coupling to CDTire/Thermal in advanced handling applications

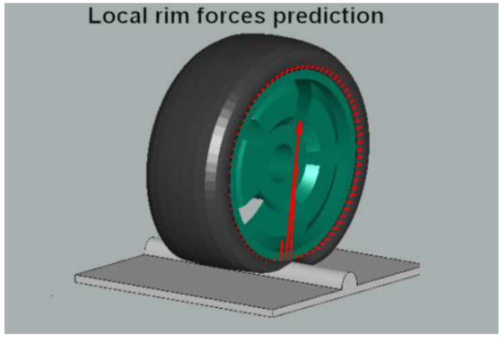
Mechanical models

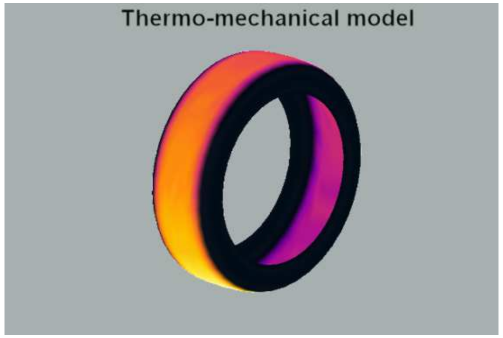
- **CDTire/Thermal** – 3D thermo-dynamical model to predict temperature creation and propagation in a tire

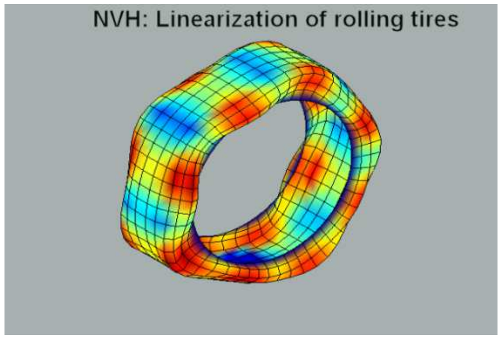
Thermo-dynamical model

- **CDTire/NVH** – a software toolbox to derive linear models out of CDTire/3D with rotation
- **CDTire/PI** – a software tool for perform parameter identification for the CDTire submodels

Stand-alone tools

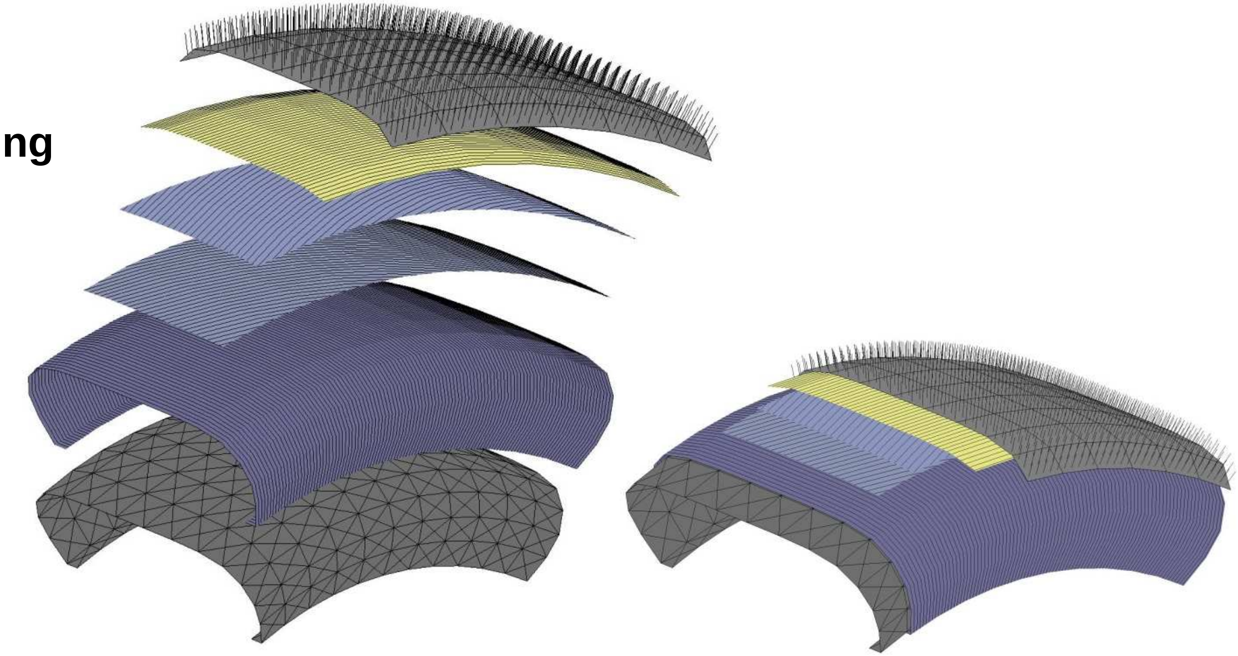




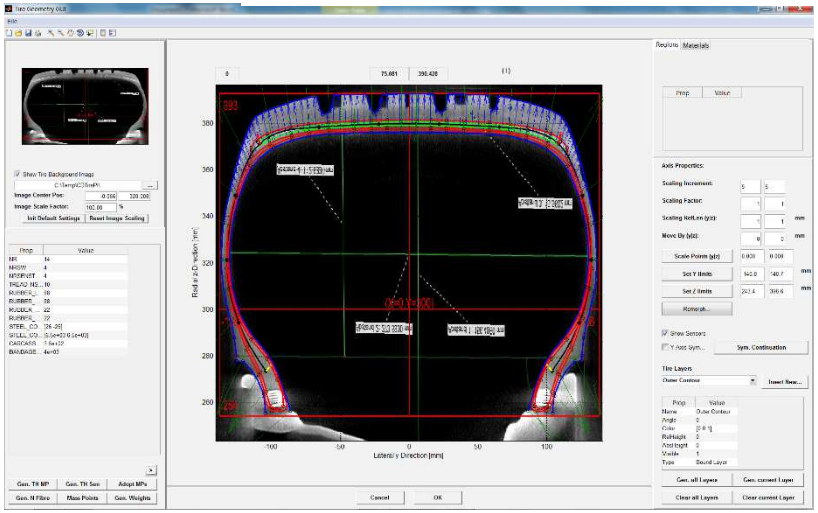


CDTire/3D

- **Functional layer modeling**
  - Tread (brush type)
  - Cap ply
  - Belt 1
  - Belt 2
  - Carcass
  - Innerliner + matrix



- **Condensed into one shell**
- **Highlights**
  - Strict separation of material and geometry
  - Re-mounting on different rim width
  - **Innerliner geometry fully available for inflation pressure application**



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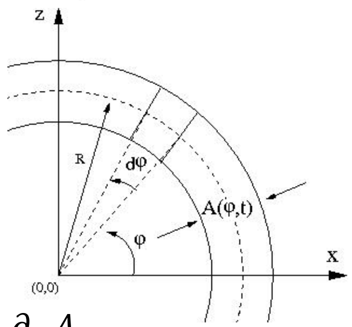
Cavity models

- **Time dependently prescribed pressure**
  - Inflation pressure given $$p = p(t)$$
- **Ideal gas equation**
  - Inflation pressure statically calculated $$p = \frac{p_0\, V_0}{V}$$
- **Isentropic compressible Euler equation**
  - Pipe flow with variable cross area
  - Conservation of mass
  - Conservation of momentum
  - Isentropic process



$$\partial_t(\rho\, A) + \frac{1}{R}\partial_\varphi(\rho\, A\, v) = 0$$

$$\partial_t(\rho\, A\, v) + \frac{1}{R}\partial_\varphi(\rho\, A\, v^2 + p\, A) = p\, \frac{1}{R}\partial_\varphi A$$

$$p = p(\rho)$$

  - with $\alpha = \rho\, A$
  - and $\mu = \rho\, A\, v$
  - and $p(\rho) = c^2 \rho$ rewrite as

$$\partial_t \alpha + \frac{1}{R}\partial_\varphi \mu = 0$$

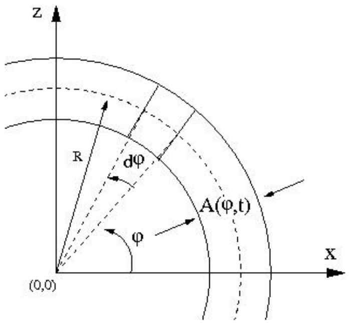
$$\partial_t \mu + \frac{1}{R}\partial_\varphi\left(\frac{\mu^2}{\alpha} + c^2 \alpha\right) = c^2 \alpha \frac{1}{R}\frac{\partial_\varphi A}{A}$$

$$p = c^2 \frac{\alpha}{A}$$

Cavity models: Euler flow model in detail

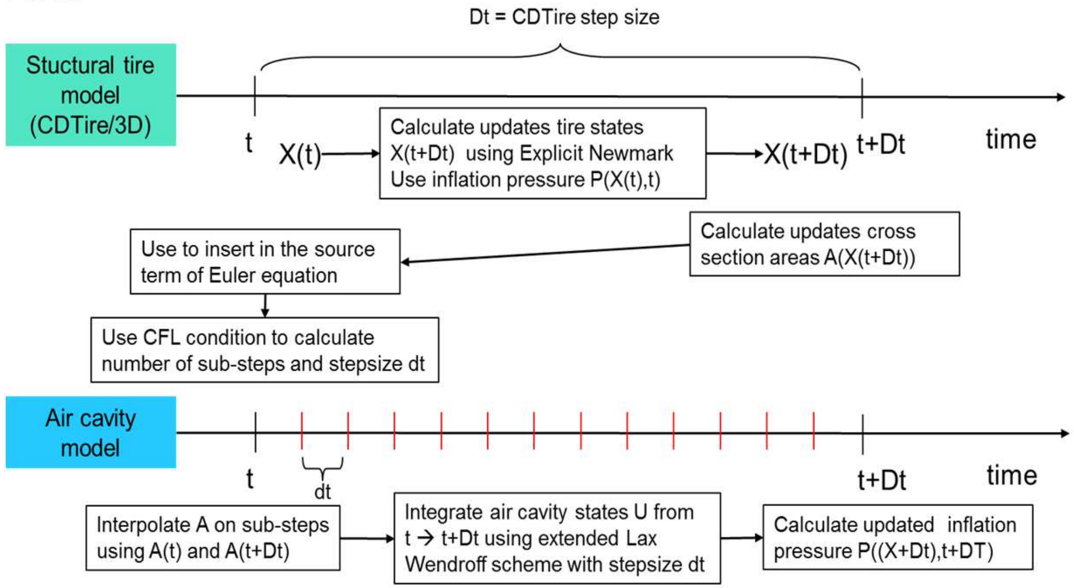
- **(Main) model parameter**
  - Velocity of sound c
  - Effective tube radius R
  - Sub-division $\Delta x = N\,\Delta s$
  - Courant-Friedrichs-Lewy $CFL = c\dfrac{\Delta t}{\Delta x} < 1$

$$\partial_t \alpha + \frac{1}{R}\partial_\varphi \mu = 0$$
$$\partial_t \mu + \frac{1}{R}\partial_\varphi\left(\frac{\mu^2}{\alpha} + c^2\alpha\right) = c^2\alpha\frac{1}{R}\frac{\partial_\varphi A}{A}$$
$$p = c^2\frac{\alpha}{A}$$



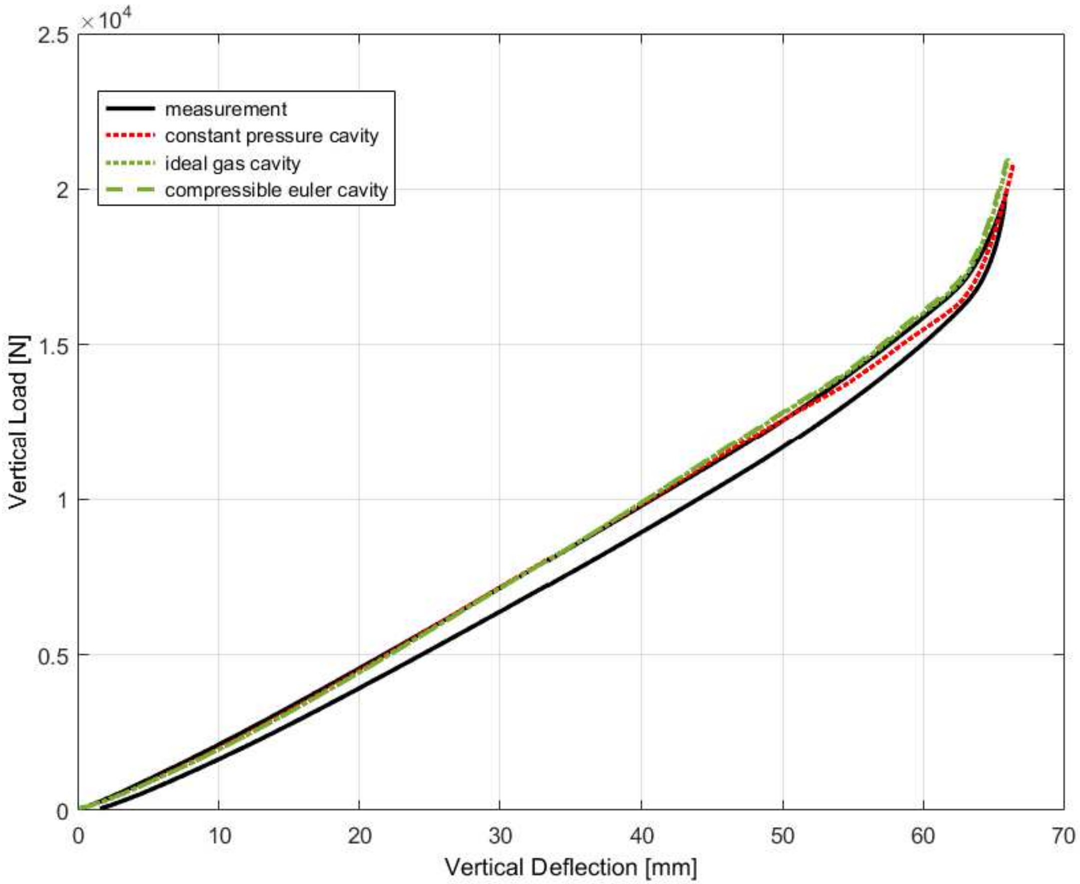
- **Interaction with mechanical model**
  - Local pressure p
  - Cross section area A

- **Co-simulation scheme**
  - Top level: MBS solver
  - Int. level: tire model
  - Bot.level: cavity mode
  - Scheme: Lax-Wendroff with source term



Cavity models: Vertical stiffness comparisons

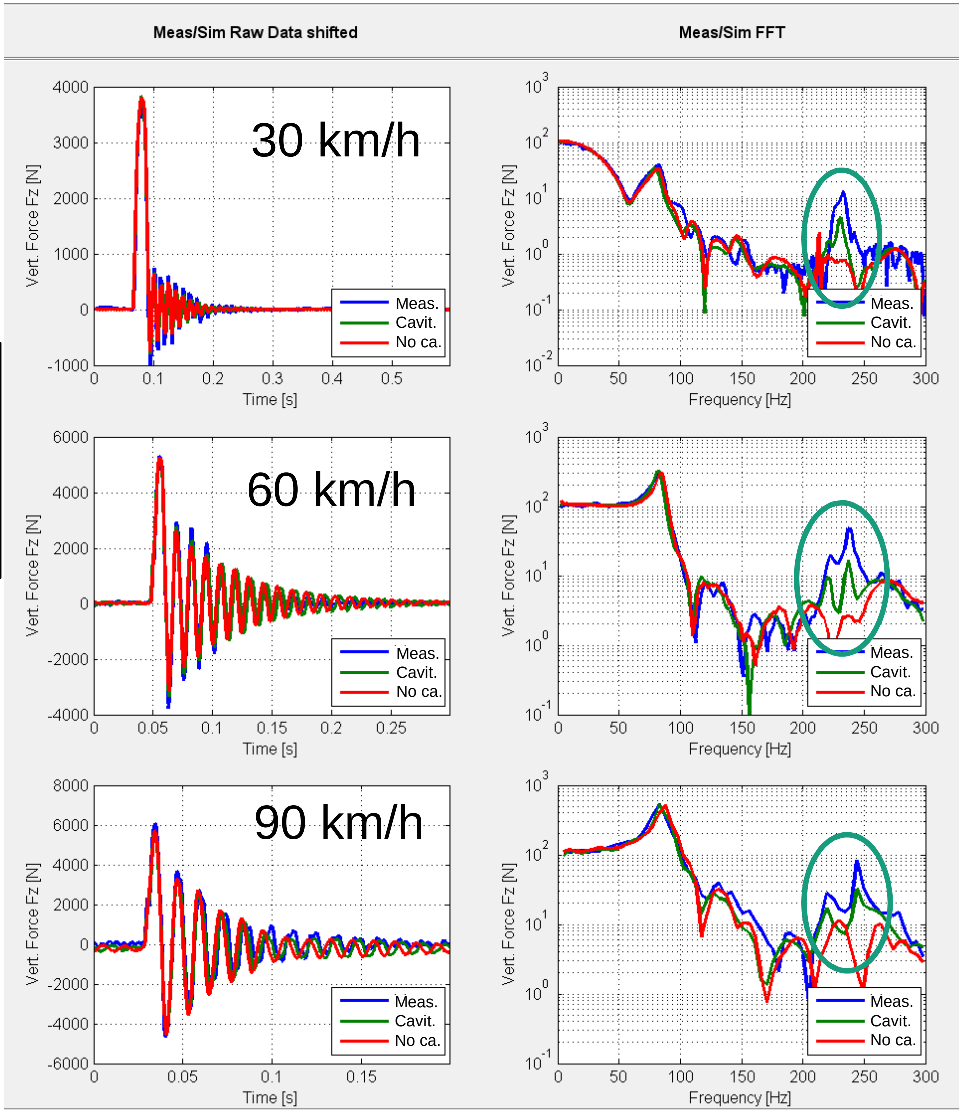
- **Vertical stiffness**
  - flat surface
  - Preload 0 N .. 21000 N
  - Velocity 0 km/h
- Constant pressure **does not** capture decrease in volume
- Ideal gas and compressible Euler equation models **do**
- For quasi-static scenarios ideal gas equation model **seems to suffice**



Cavity models: Cleat run comparisons

- **Vertical force**
  - 20x20 mm cleat
  - Preload 2400 N
  - 30 / 60 / 90 km/h

- Measurement
- Euler equation
- Constant pressure (= Ideal gas)



- Observe **cavity mode** around 230 Hz
- Observe **split** due to rotational vel. increase (Doppler effect)
- **Only Euler equation model captures this correctly**

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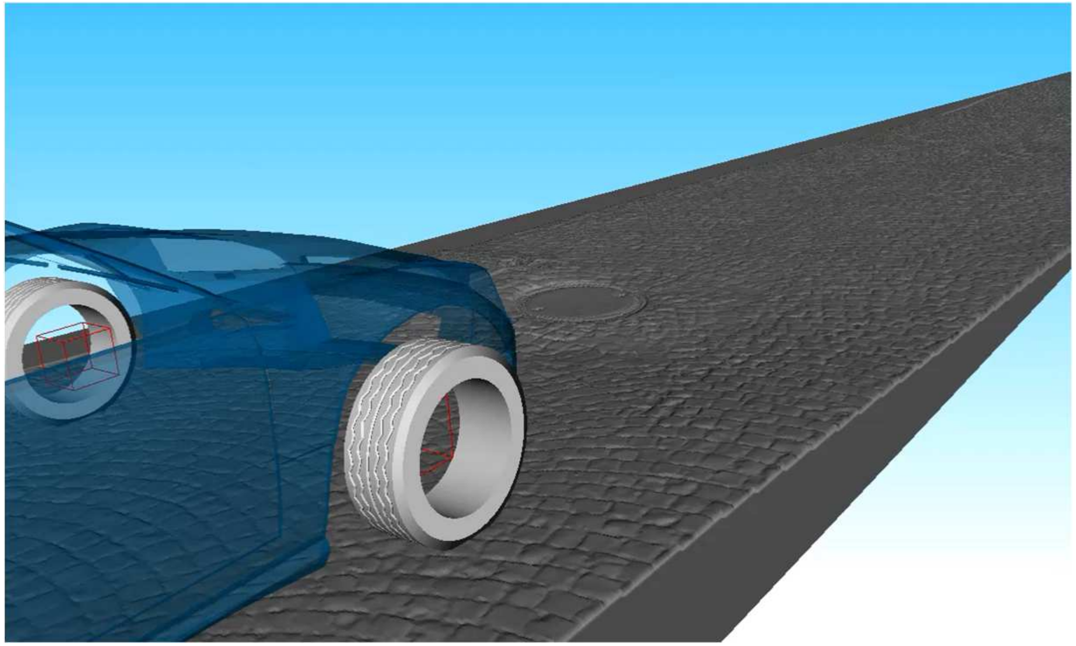
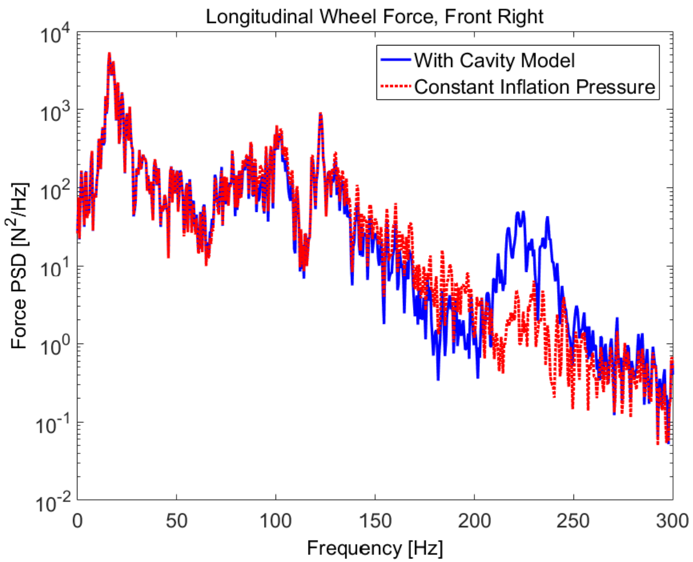
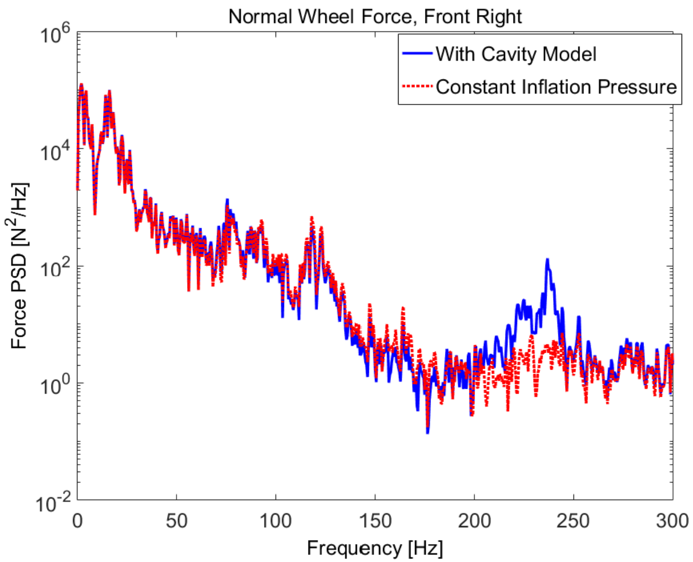
CDTire/3D

- **Application example**
  - Rough road
  - 50 km/h
  - PSD of spindle forces







Short summery of Euler flow cavity model

CDTire/3D

Euler Flow

Transient Non-Linear: MBS Solvers

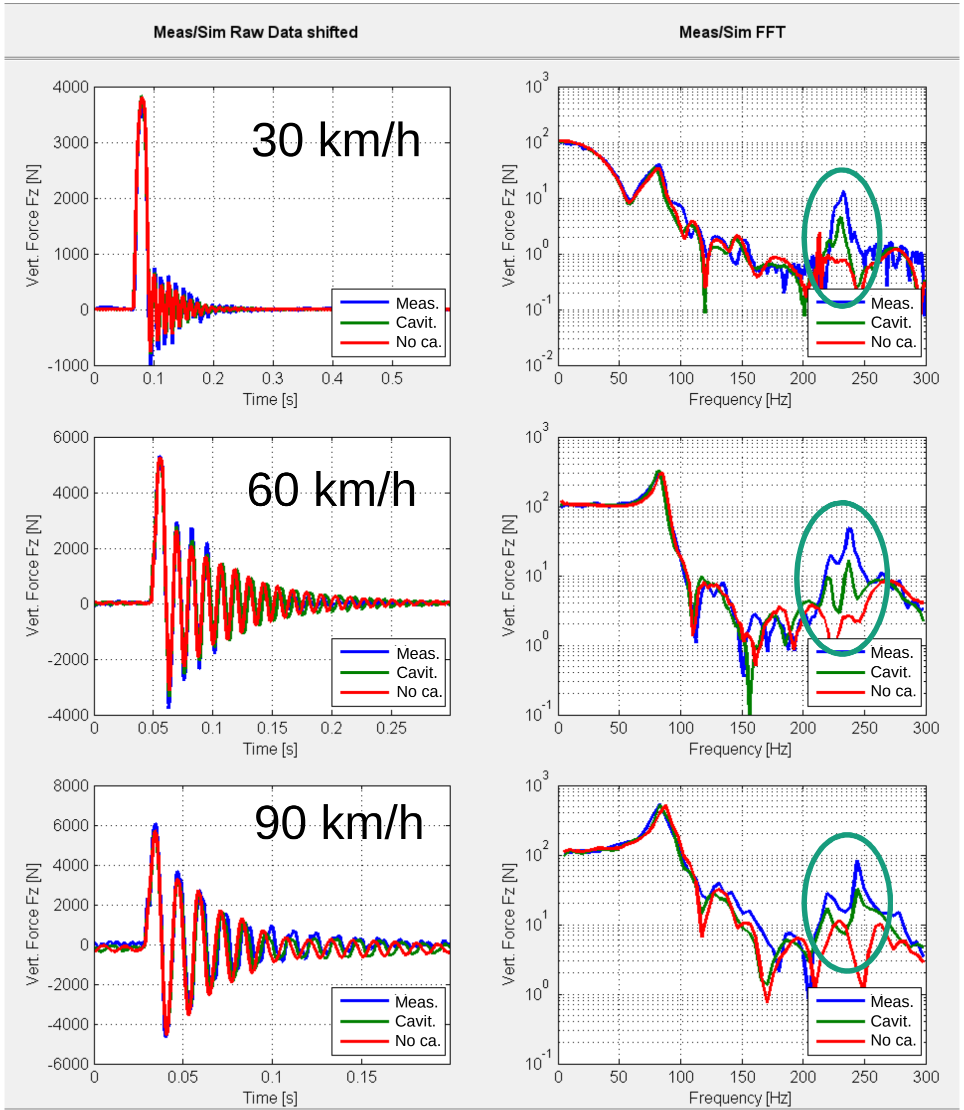
- Modeling explained

$$\partial_t \alpha + \frac{1}{R}\partial_\varphi \mu = 0$$

$$\partial_t \mu + \frac{1}{R}\partial_\varphi\left(\frac{\mu^2}{\alpha} + c^2\alpha\right) = c^2\alpha\frac{1}{R}\frac{\partial_\varphi A}{A}$$

$$p = c^2\frac{\alpha}{A}$$

- Numerics explained
  - Conservation form
  - Lax-Wendroff
  - CFL condition

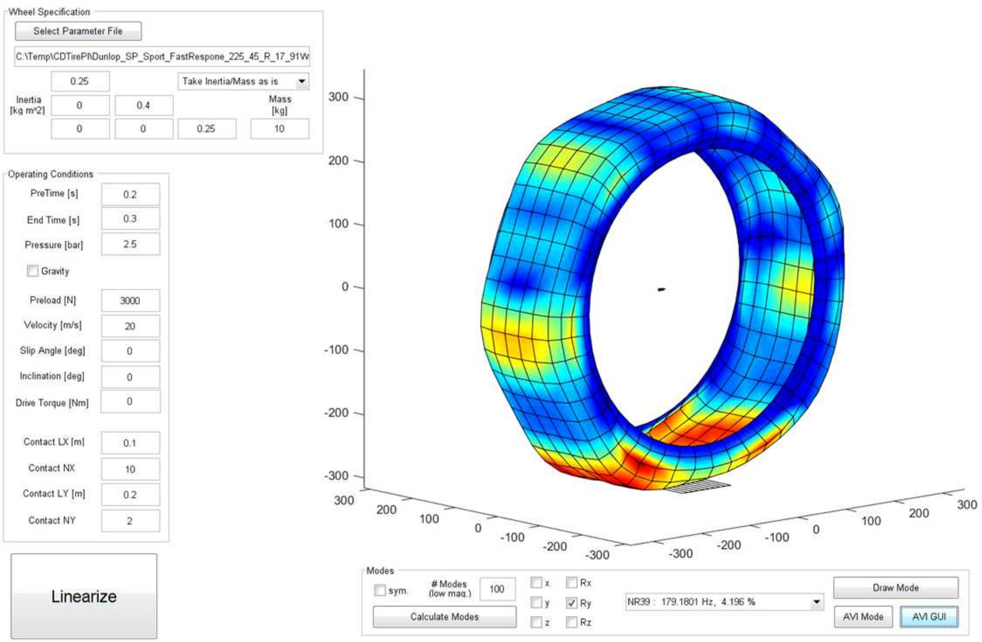


Linearization including rotational effects

CDTire/3D

Linearization: CDTire/NVH

- M. Baecker, A. Gallrein, M. Roller: Noise, vibration, harshness model of a rotating tyre, Vehicle System Dynamics Vol.54 – Issue 4, pp. 474-491, 2016, doi: 10.1080/00423114.2016.1158844



Linearization including rotational effects with cavity

CDTire/3D

Euler Flow

⇓

Linearization: CDTire/NVH

$$\partial_t \alpha + \frac{1}{R}\partial_\varphi \mu = 0$$

$$\partial_t \mu + \frac{1}{R}\partial_\varphi\left(\frac{\mu^2}{\alpha} + c^2\alpha\right) = c^2\alpha\frac{1}{R}\frac{\partial_\varphi A}{A}$$

$$p = c^2\frac{\alpha}{A}$$

⇓ Differentiation

$$\partial_{tt}\alpha \;=\; \frac{c^2}{R^2}\partial_{\varphi\varphi}\alpha - \frac{c^2}{R}\partial_\varphi\left(\alpha\frac{1}{R}\frac{\partial_\varphi A}{A}\right)$$

⇓ Arbitrary Lagrangian Eulerian
Method of Lines

$$M_T\ddot{x}_T = f_{str}(x_T, \dot{x}_T, \alpha) + f_{gyr}(x_T, \dot{x}_T, \omega)$$
$$\ddot{\alpha} = g_{cav}(\alpha, x_T) \quad + g_{gyr}(\alpha, x_T, \omega)$$

⇓ Finite Differencing

M, C, K matrices

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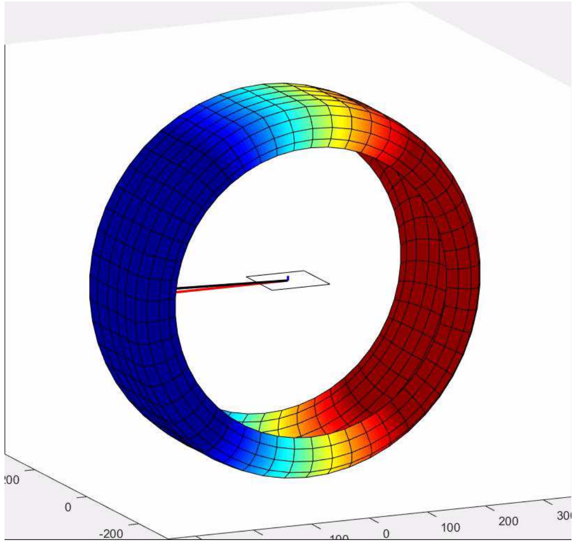
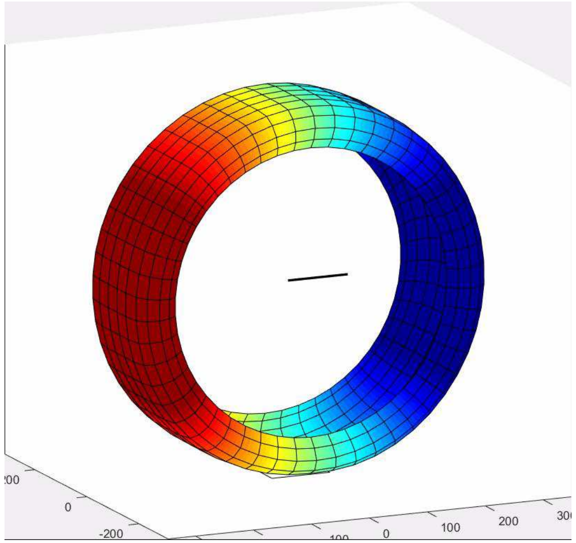
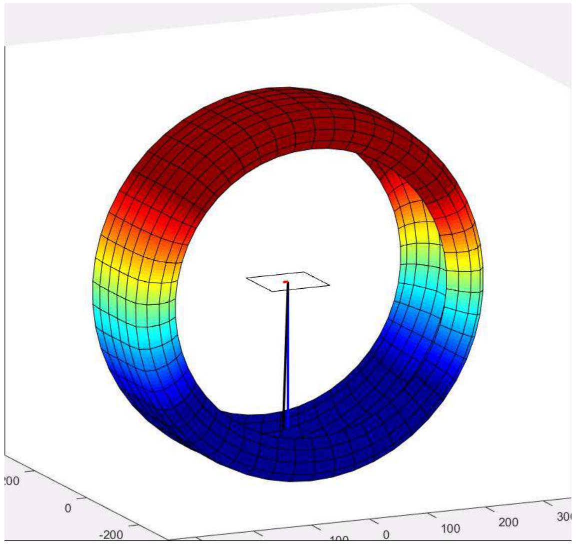
free tire | w = 0 km/h / r | loaded tire 2400 N



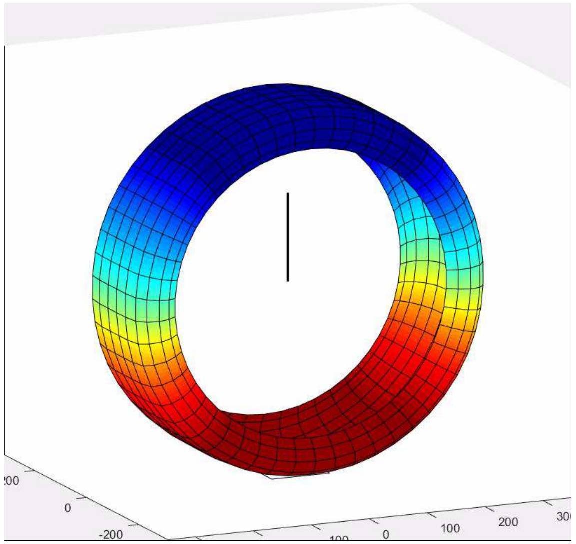
225.4 Hz



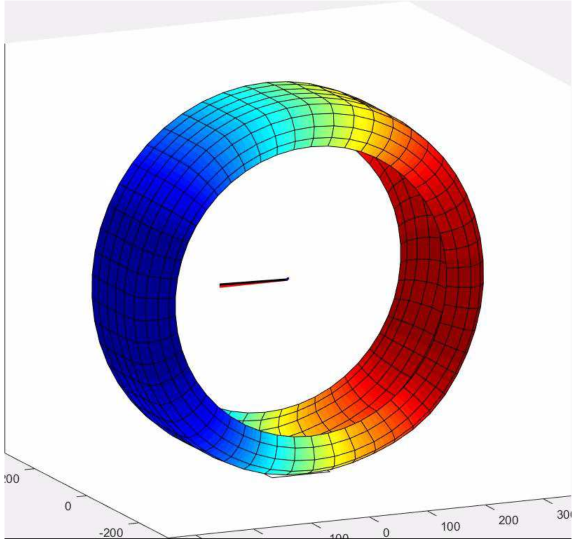
226.5 Hz



228.4 Hz

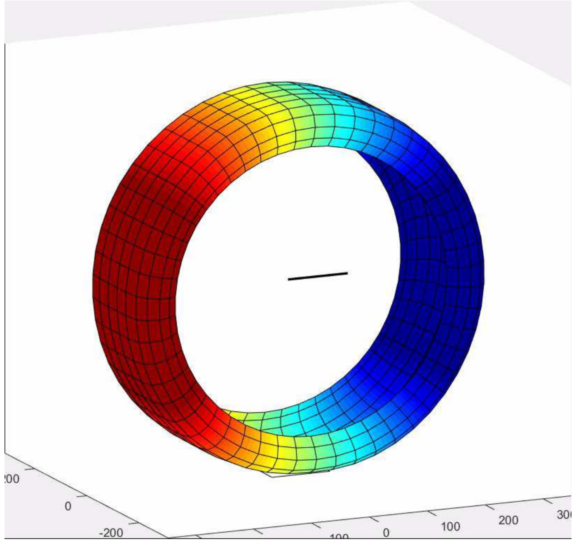


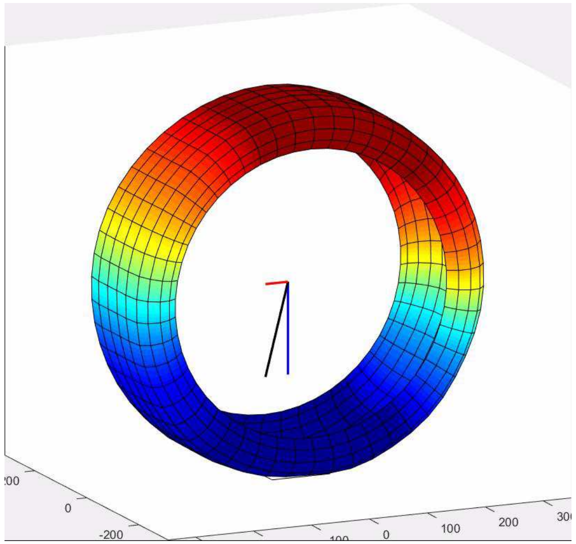
w = 90 km/h / r   loaded tire 2400 N   w = 0 km/h / r



213.1 Hz

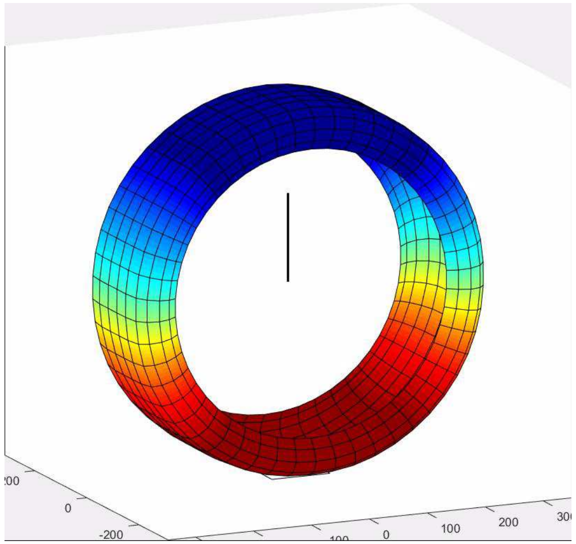
225.4 Hz





238.9 Hz

228.4 Hz



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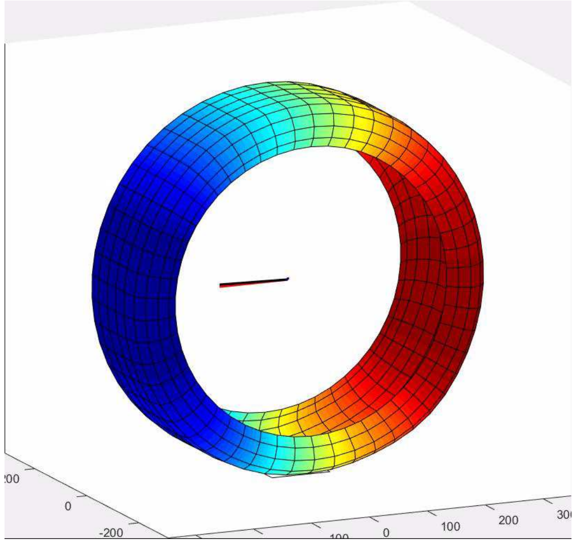
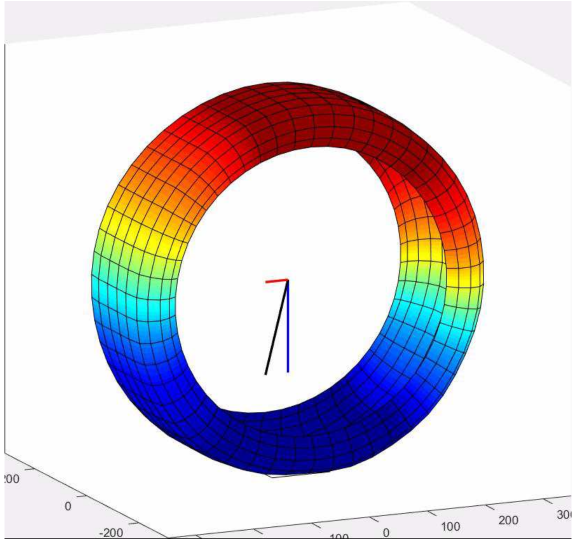
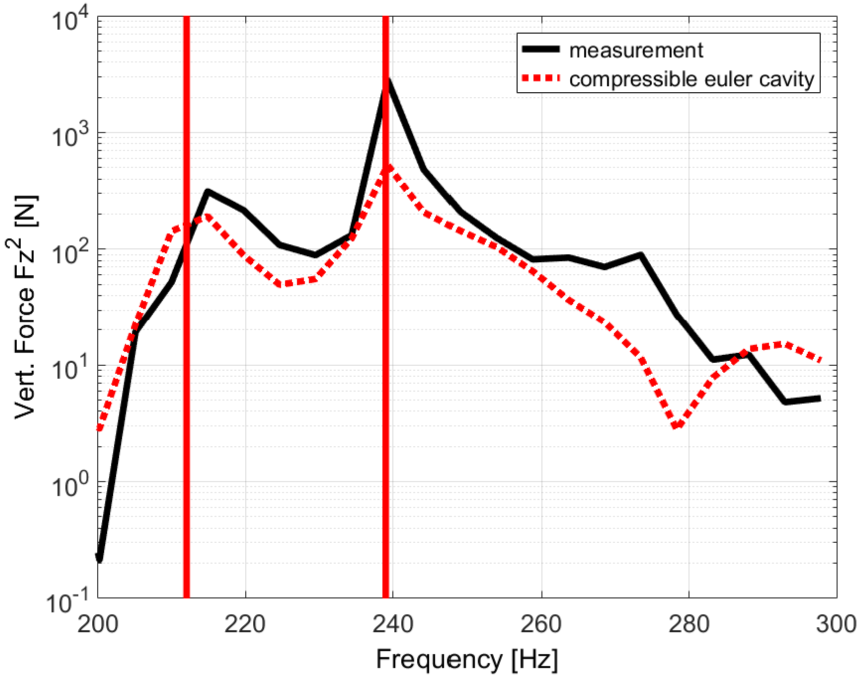
w = 90 km/h / r   loaded tire 2400 N   w = 0 km/h / r



213.1 Hz



238.9 Hz



Summary

- Compared cavity models
  - Prescribed inflation pressure
  - Ideal gas equation
  - Euler flow equation

- Observations
  - Prescribed IP only for moderate loads and frequency range below cavity modes
  - Ideal gas equation only for frequency range below cavity modes

- Validations
  - Transient Euler flow with cleat runs
  - Derived linearized Euler flow with cleat runs

- Outlook
  - Temperature dependency
  - Pressure regulation

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Thank you for your attention !

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