Enhancing the Modeling of Train-Track Interaction by Including the Structural Dynamics of Wheelsets and Track

Status of DLR SIMPACK Prototype Implementation

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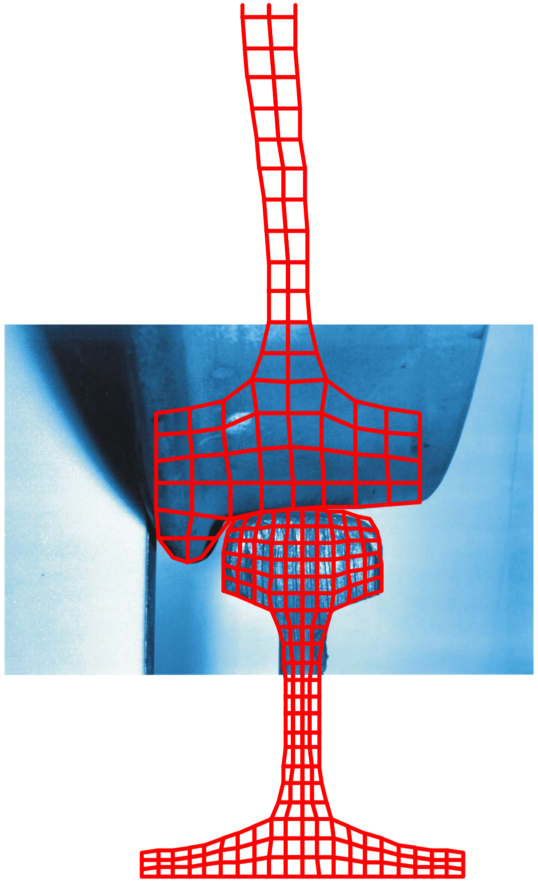
Outline

- Motivation
- The flexible wheelset
- The flexible track
- Conclusion and outlook



Motivation

- MBS modeling is well established for railway dynamics
- Implementation of flexible structures enlarges frequency range
- Aim: Enhancing the modeling of train-track interaction up to frequency ranges relevant for noise generation
- Also important for
  - accurate contact calculations (wear)
  - dynamic effects causing
    - traction control problems
    - non-uniform wear (corrugation)
  - strength calculation of wheelsets
  - noise prediction
- Flexible modeling of wheelsets and track-structure requires special approaches because of moving loads

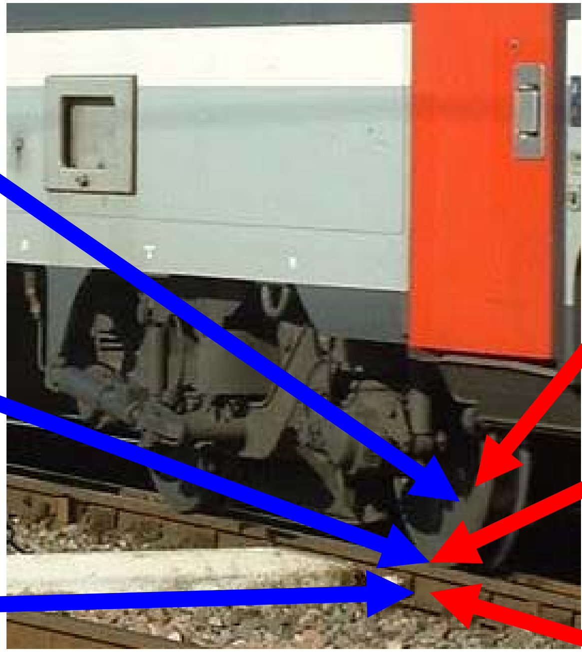
Enhancing the vehicle-track modeling

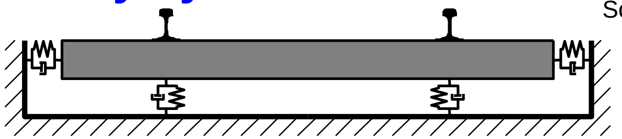
Standard modeling (SIMPACK)

Wheelset: Rigid body

Hertzian (elliptic) contact

Track: Rigid body system

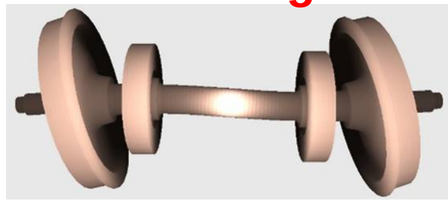




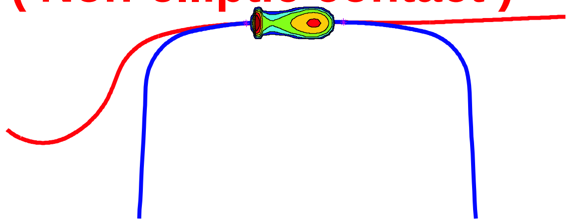
Source: www.railfaneurope.net

Modeling enhancements for extended frequency range

Flexible rotating wheelset



(Non-elliptic contact)



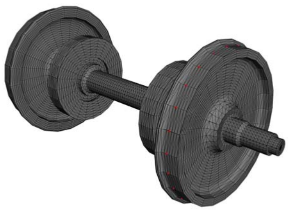
Flexible rail

Approaches for the flexible wheelset

- Axle: Beam, wheels & brake discs: Rigid bodies

- Composition of rigid bodies and discrete springs

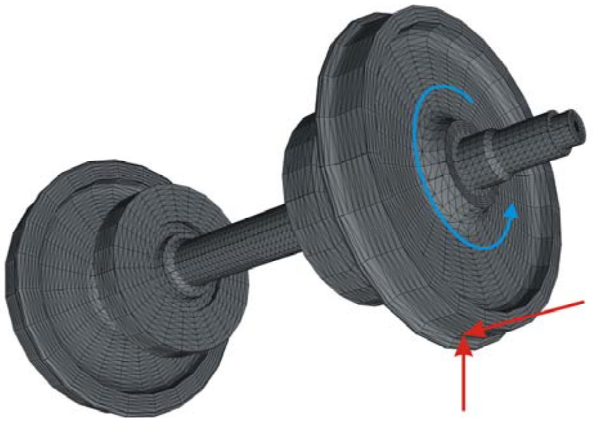
- Modally condensed FE structure *without* overturning



- Modally condensed FE structure ***with full*** consideration of overturning
  - Interpolation
  - **Moved marker with analytic shape function**

The flexible wheelset

- Rotating structure with non-rotating loads → *moved marker*



- Exploiting the characteristics of rotationally symmetric structures
  - Each eigenmode has *one and only one* periodicity k_i

$$\mathbf{U}_i(r,\phi,y) = \begin{bmatrix} T_{i,A}(r,y) \\ V_{i,A}(r,y) \\ R_{i,A}(r,y) \end{bmatrix} \cos(k_i\phi) + \begin{bmatrix} T_{i,B}(r,y) \\ V_{i,B}(r,y) \\ R_{i,B}(r,y) \end{bmatrix} \sin(k_i\phi)$$

$$\mathbf{U}_i(r,\phi,y) = \mathbf{u}_{i,A}(r,y)\cos(k_i\phi) + \mathbf{u}_{i,B}(r,y)\sin(k_i\phi)$$

Eigenmodes of a rotational symmetric structure

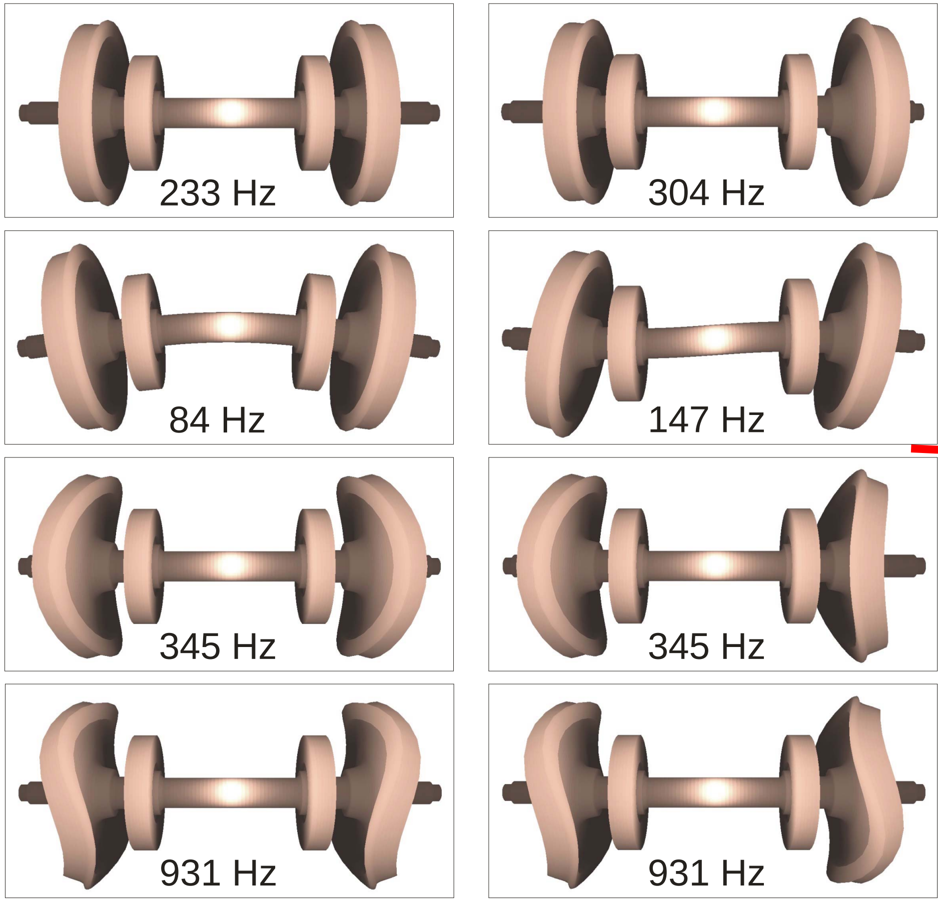
symmetric | antimetric

$k_i = 0$
(umbrella modes)

$k_i = 1$
(bending modes)

$k_i = 2$
(wheel modes)

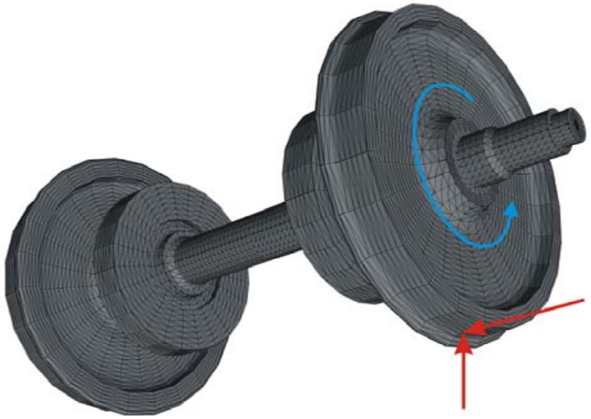
$k_i = 3$
(wheel modes)



No interaction between wheel and axle

The flexible wheelset

- Rotating structure with non-rotating loads → *moved marker*



- Exploiting the characteristics of rotationally symmetric structures
  - Each eigenmode has *one and only one* periodicity k_i

$$\mathbf{U}_i(r,\phi,y) = \mathbf{u}_{i,A}(r,y)\cos(k_i\phi) + \mathbf{u}_{i,B}(r,y)\sin(k_i\phi)$$

  - Double eigenmodes for

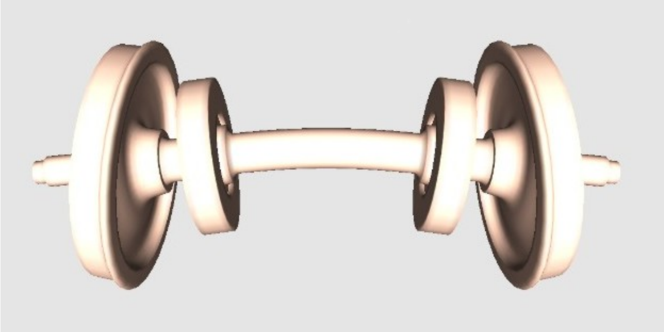
$$\mathbf{U}_{i1}(r,\phi,y) = \mathbf{u}_{i,A}(r,y)\cos(k_i\phi) + \mathbf{u}_{i,B}(r,y)\sin(k_i\phi)$$
$$\mathbf{U}_{i2}(r,\phi,y) = \mathbf{u}_{i,A}(r,y)\sin(k_i\phi) - \mathbf{u}_{i,B}(r,y)\cos(k_i\phi)$$

Eigenmodes of a rotational symmetric structure

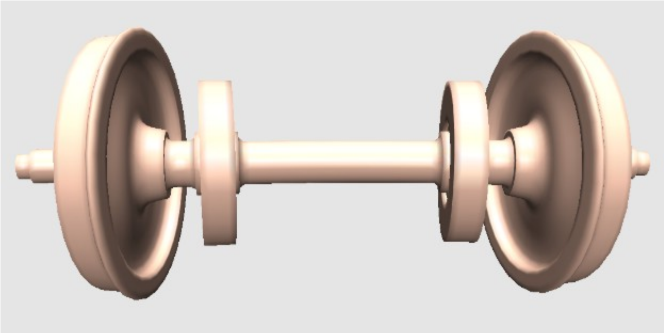
Damped rotational symmetric system: $\mathbf{M}\ddot{\mathbf{y}} + \mathbf{D}\dot{\mathbf{y}} + \mathbf{K}\mathbf{y} = \mathbf{0}$, $\mathbf{D} = \mathbf{D}^T$, $\mathbf{K} = \mathbf{K}^T$

→ *Double eigenvalues and eigenmodes for* $k_i \neq 0$ *(spatial orientation)*

$$\mathbf{U}_{i1}(r,\phi,y) = \mathbf{u}_{i,A}(r,y)\cos(k_i\phi) + \mathbf{u}_{i,B}(r,y)\sin(k_i\phi)$$

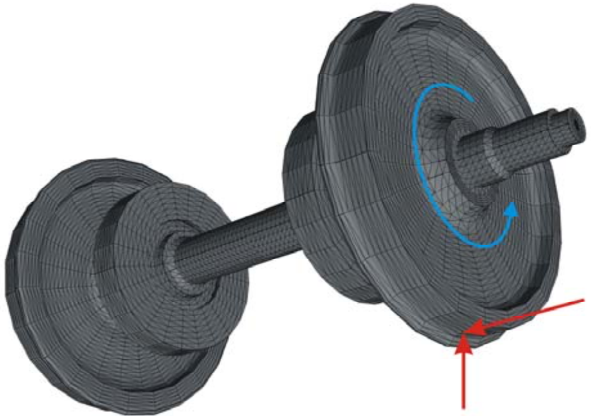


$$\mathbf{U}_{i2}(r,\phi,y) = \mathbf{u}_{i,A}(r,y)\sin(k_i\phi) - \mathbf{u}_{i,B}(r,y)\cos(k_i\phi)$$



The flexible wheelset

- Rotating structure with non-rotating loads → *moved marker*



- Exploiting the characteristics of rotationally symmetric structures
  - Each eigenmode has *one and only one* periodicity k_i

    $$\mathbf{U}_i(r,\phi,y) = \mathbf{u}_{i,A}(r,y)\cos(k_i\phi) + \mathbf{u}_{i,B}(r,y)\sin(k_i\phi)$$

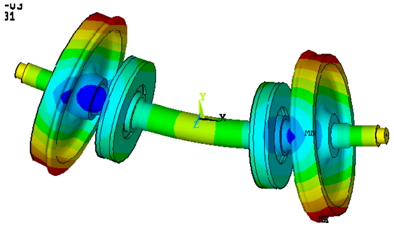
  - Double eigenmodes for

    $$\begin{aligned}\mathbf{U}_{i1}(r,\phi,y) &= \mathbf{u}_{i,A}(r,y)\cos(k_i\phi) + \mathbf{u}_{i,B}(r,y)\sin(k_i\phi)\\ \mathbf{U}_{i2}(r,\phi,y) &= \mathbf{u}_{i,A}(r,y)\sin(k_i\phi) - \mathbf{u}_{i,B}(r,y)\cos(k_i\phi)\end{aligned}$$

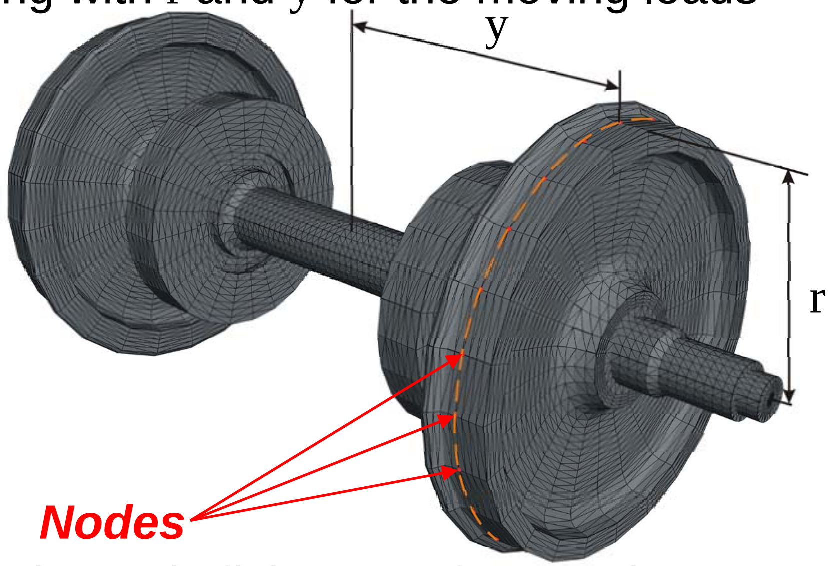
  - Distribution of the deformations by an *analytical function*
- Setting the current value from the overturning angle $\phi = \theta_0 - \chi(t)$ → *variable angular velocity of the wheelset possible*

Workflow for the flexible wheelset

- Analysis of the structural dynamics of the wheelset
  → Result: SID file



- Defining a ring with r and y for the moving loads

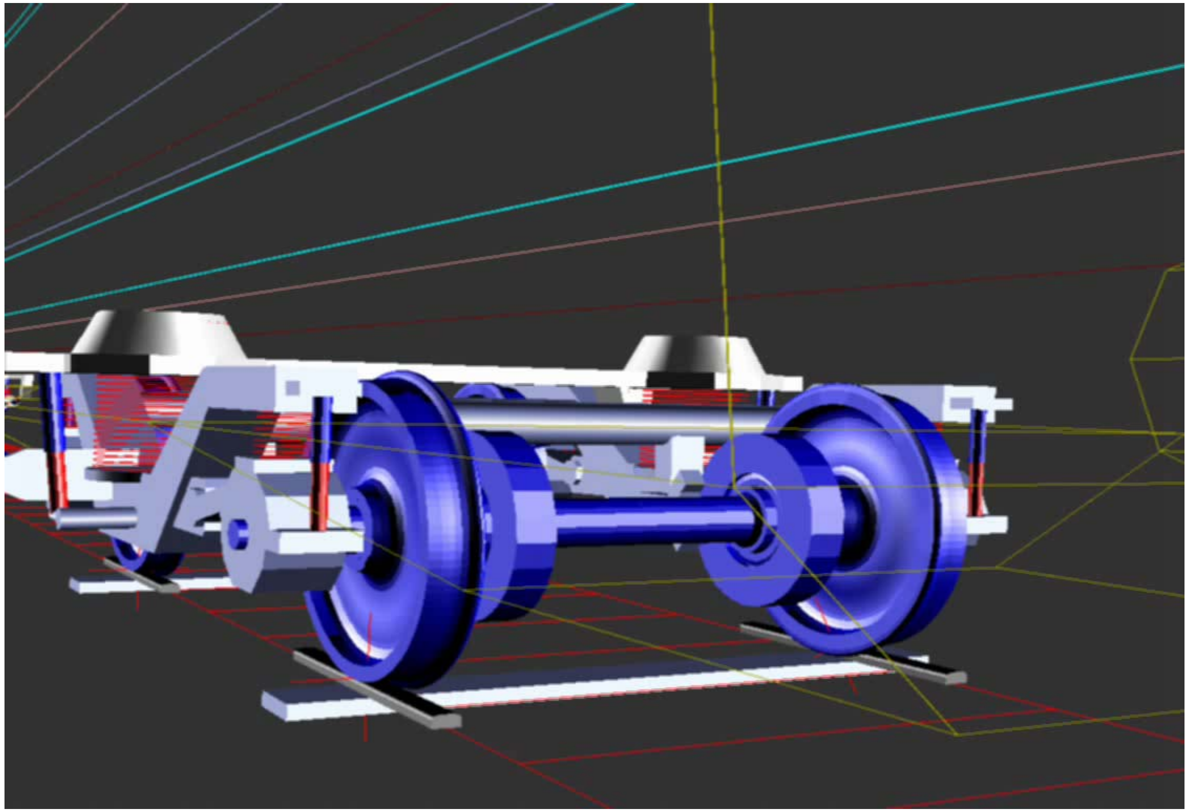


- Analyzing of the periodicity from deformations at nodes on the ring
  → Result: Additional input file
- Usual coupling of the wheel rail contact to the moved marker

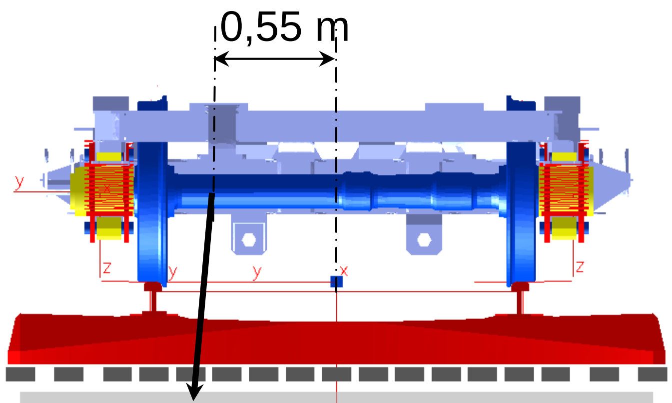
Flexible Wheelset - Example of use (1):

Hunting motion with flexible wheelset on rigid track (limit cycle)

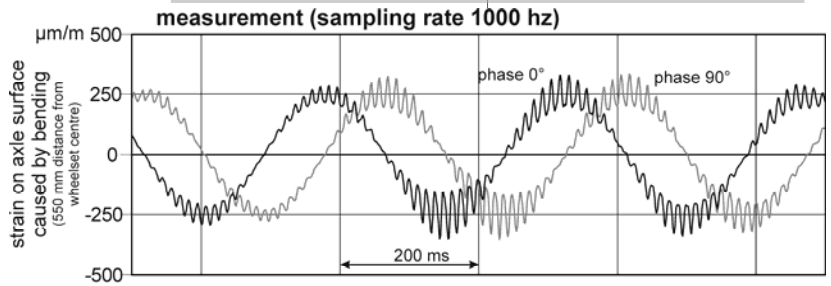
- Speed: 432 km/h
- Critical speed in the same range (but slightly lower)
- Change of contact position and contact patch geometry
- Elastic deformation of the wheel disc visible (at 20x magnification)



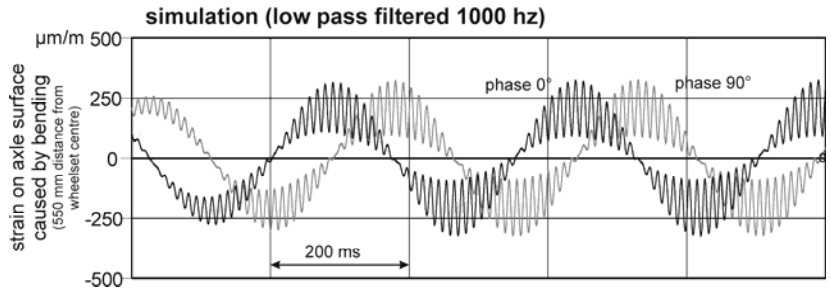
Flexible Wheelset - Example of use (2):
Friction induced vibration in curves with 80 Hz



- Curve radius 70 m
- Angle of attack ≈ 20 mrad
- Flexible standard track
- High friction level (μ ≈ 0,5)

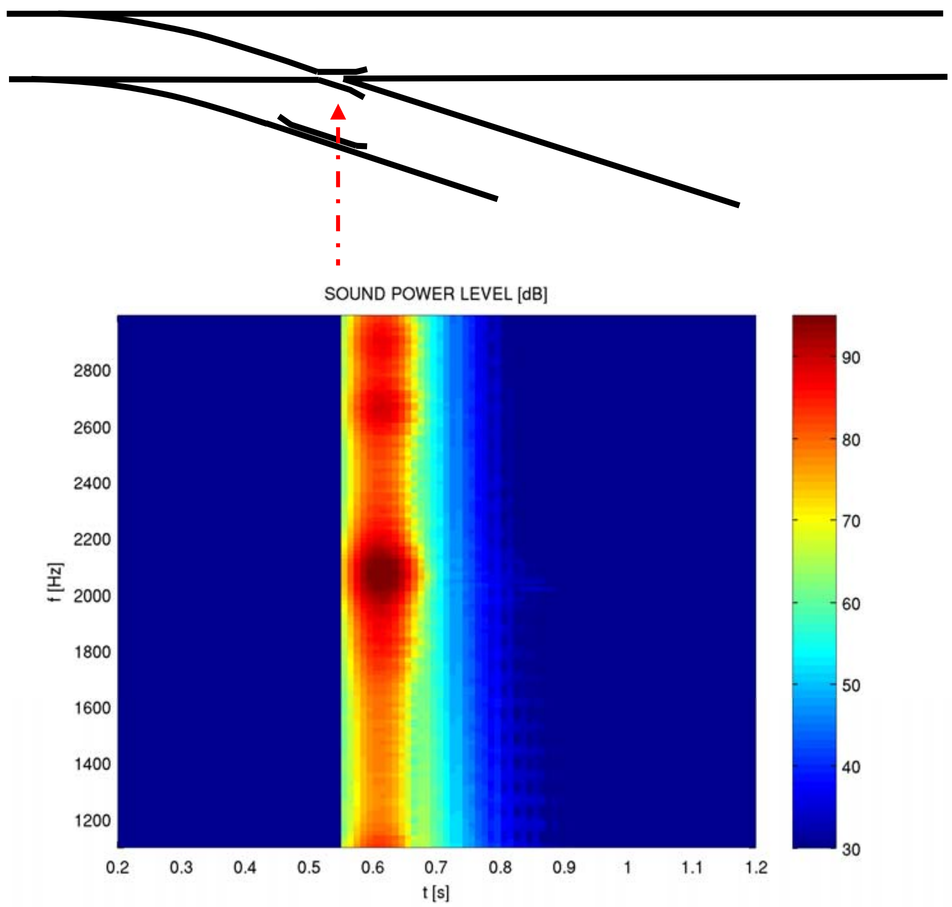


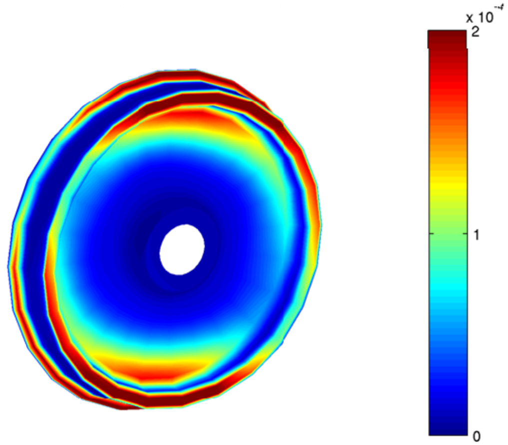
- Bending stress (wheelset axle) good accordance with measurements



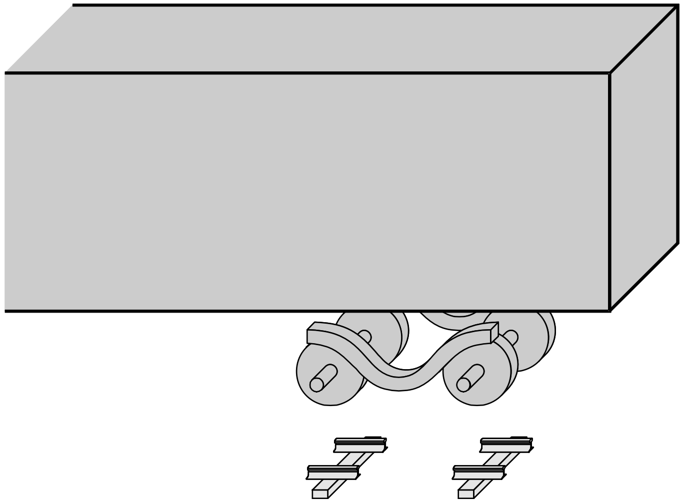
- Causation of non-uniform corrugation

Flexible Wheelset - Example of use (3):
Sound power of wheel surface at switch crossing



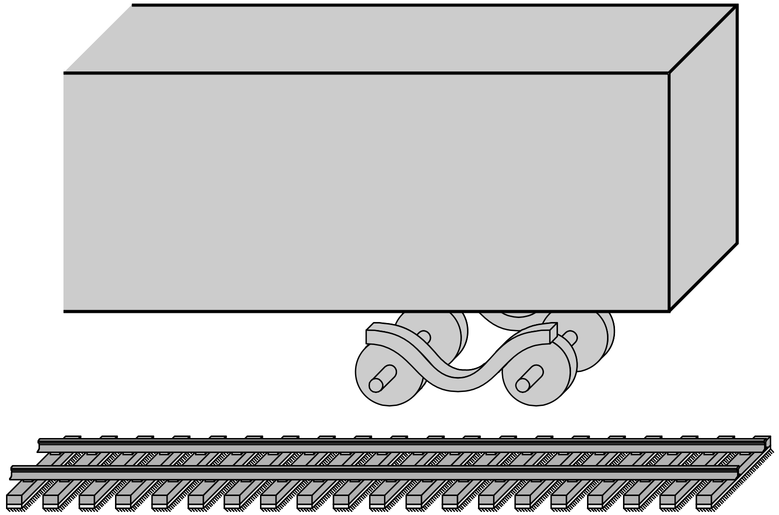


Modeling of the track



Single track elements

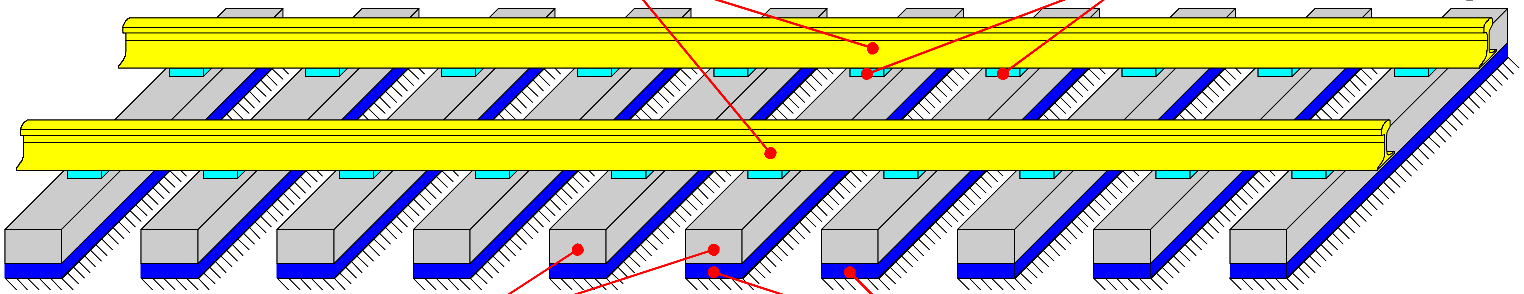
- One track element for each wheelset
- Simple modeling in the MBS formalism
- No interaction between the wheelsets



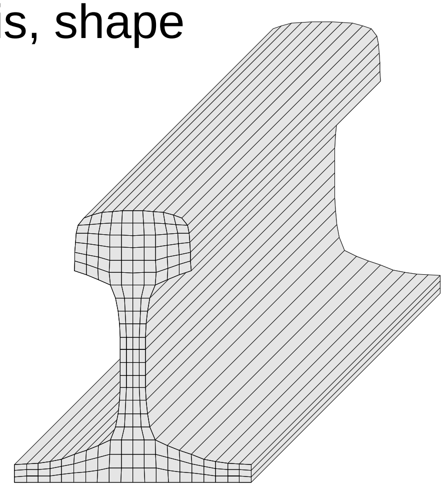
Continuous track model

- One track model for the entire vehicle
- Separate structural dynamics model
- Integration by co-simulation
- Interaction between the wheelsets
- Detailed track model
  → Modeling of the rails' acoustics

Structure of the track model

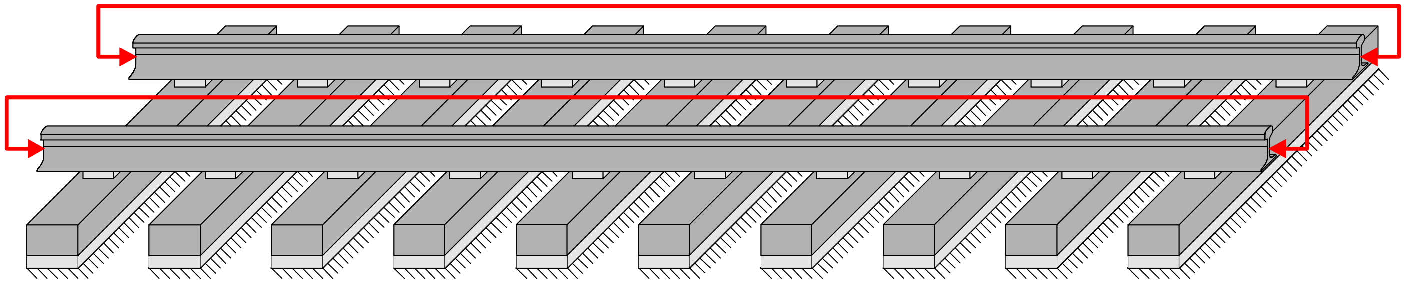


- Rails: Flexible bodies, description by modal synthesis, shape functions from 3D FE model
- Sleepers: Rigid bodies, 6 DOF
- Basis: Track model by Ripke (1995), modifications:
  - Refined FE modeling of the rails
  - Consideration of the rails' inclination
  - Pads: Distributed stiffness and damping



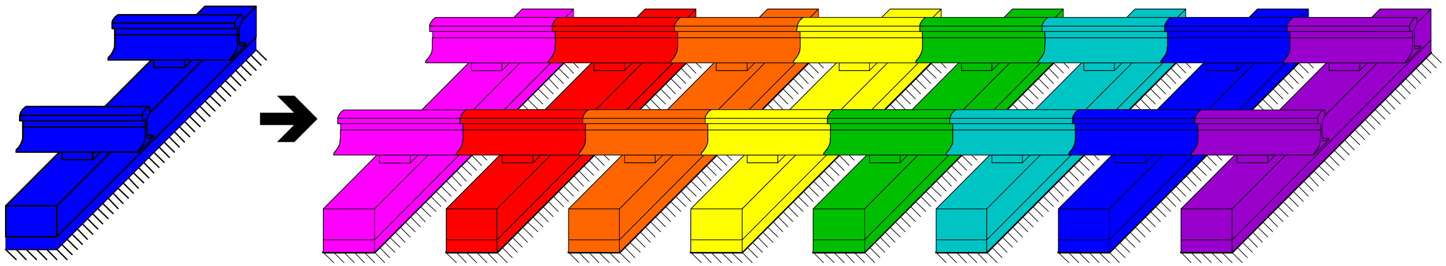
Problems of track modeling

- **Large dimension** (length of several kilometers)
  - Selection of suitable boundary conditions



Equal BCs at the ends („ring with neglected curvature")

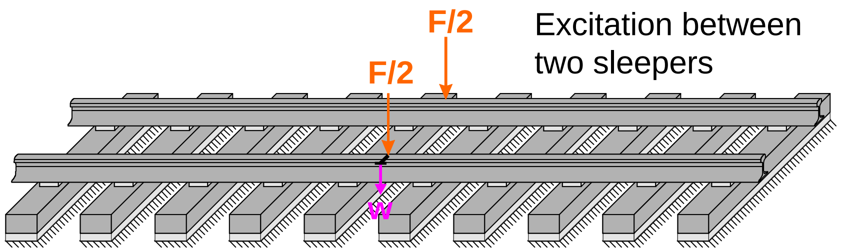
  - Exploitation of the structure's periodicity (cyclic structure)

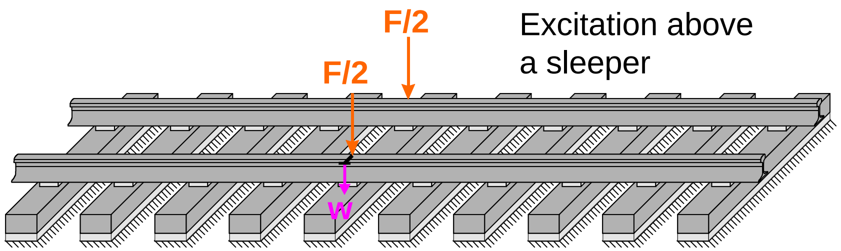


Description of the eigenvectors (shape functions) by Fourier series

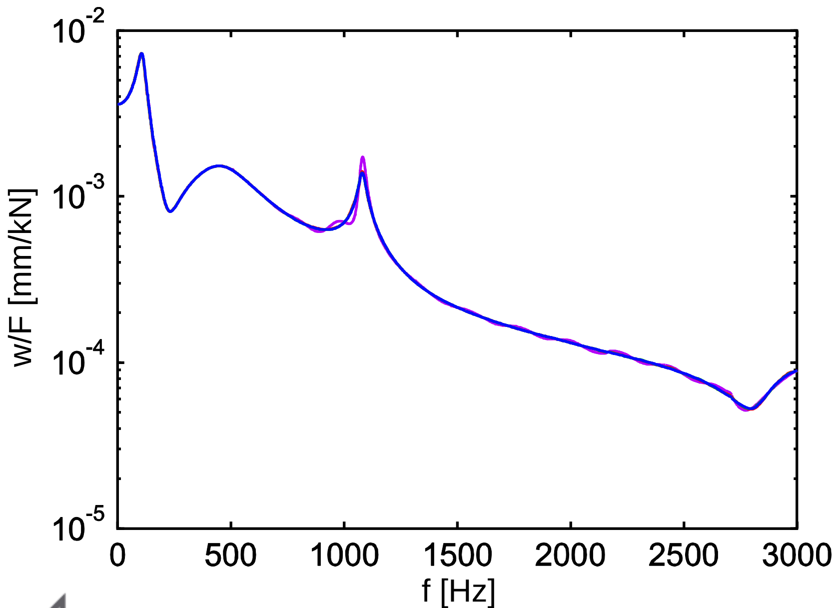
$$\left[\mathbf{M}_{\mathrm{T}}\lambda_i^2+\mathbf{D}_{\mathrm{T}}\lambda_i+\mathbf{K}_{\mathrm{T}}\right]\mathbf{u}_{\mathrm{T},i}=\mathbf{0},\ \mathbf{u}_{\mathrm{T},i}(x)=\sum_j\left[\mathbf{u}_{i,jC}\cos\left(k_j\kappa x\right)+\mathbf{u}_{i,jS}\sin\left(k_j\kappa x\right)\right],\ \kappa=\frac{2\pi}{\ell_{\mathrm{T}}}$$

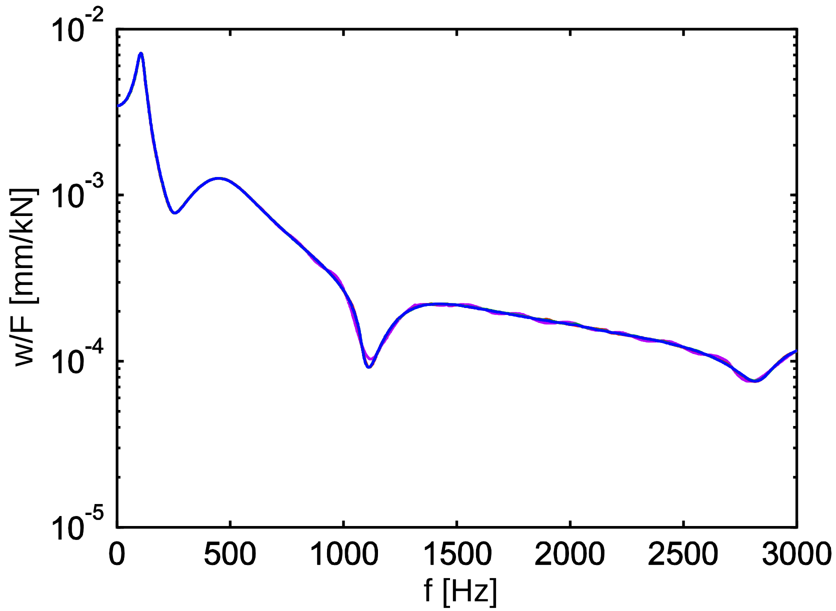
Effect of the track length: Vertical receptance



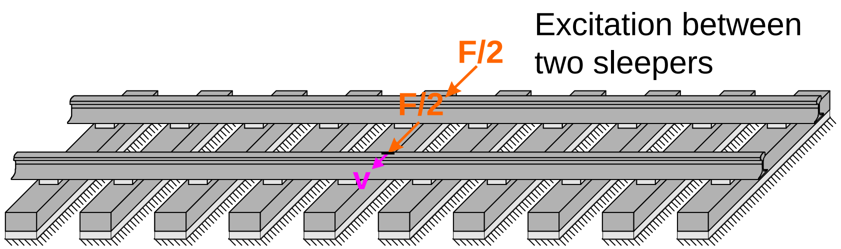


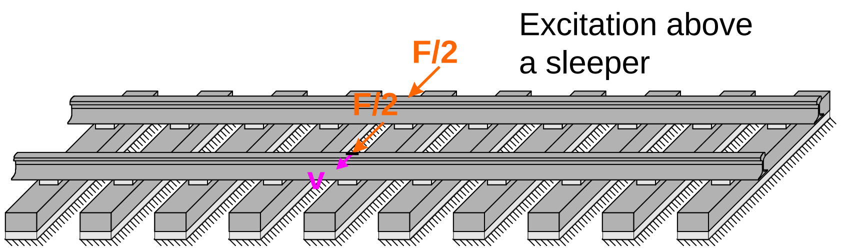
16 sleepers (9,6 m) | 32 sleepers (19,2 m) | 64 sleepers (38,4 m) | 128 sleepers (76,8 m)



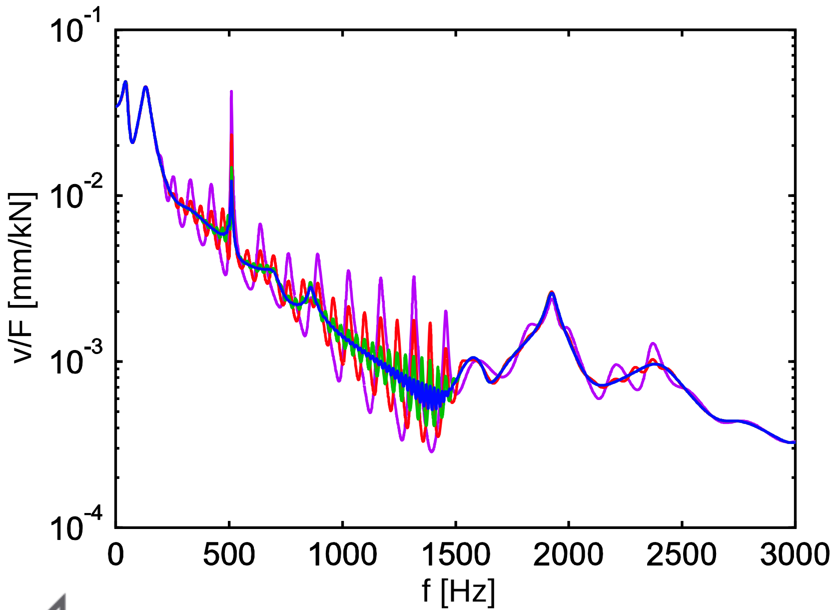


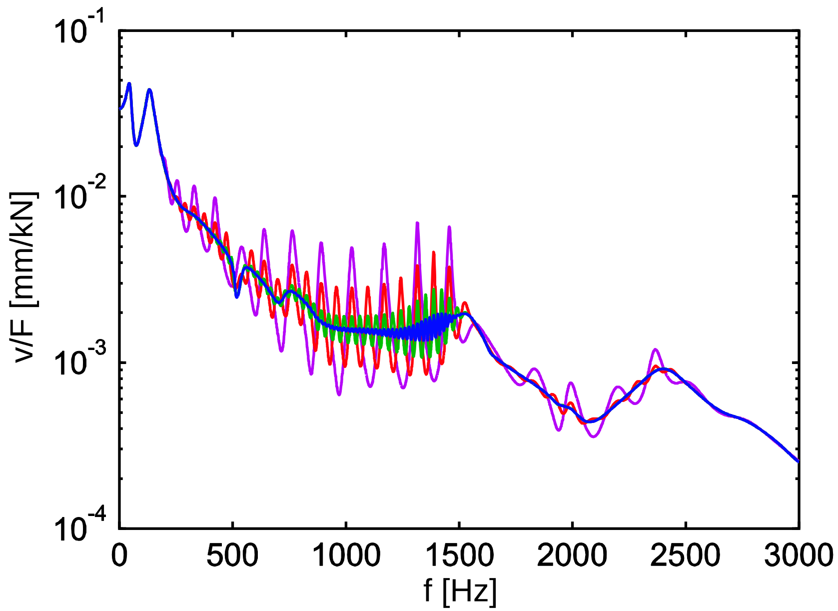
Effect of the track length: Lateral receptance



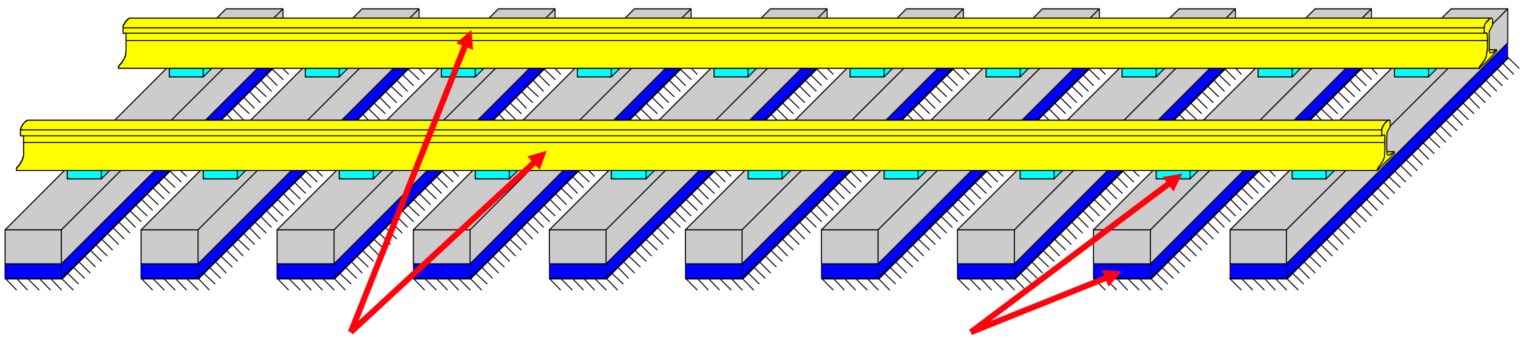


16 sleepers (9,6 m) **32 sleepers (19,2 m)** **64 sleepers (38,4 m)** **128 sleepers (76,8 m)**





Modal decomposition of the track model



High stiffness, low damping ***Low stiffness, high damping***

$$\mathbf{M}_\mathrm{T}\,\ddot{\mathbf{y}}_\mathrm{T}(t)+\mathbf{D}_\mathrm{T}\,\dot{\mathbf{y}}_\mathrm{T}(t)+\mathbf{K}_\mathrm{T}\,\mathbf{y}_\mathrm{T}(t)=\mathbf{h}_\mathrm{T}(t) \;\rightarrow\; \mathbf{D}_\mathrm{T}\neq\alpha\mathbf{M}_\mathrm{T}+\beta\mathbf{K}_\mathrm{T}$$

- 1st possibility: *Real eigenvectors* of the undamped structure

  $$\left[-\mathbf{M}_\mathrm{T}\omega_0{}^2+\mathbf{K}_\mathrm{T}\right]\mathbf{u}_i=\mathbf{0}\ ,\ \mathbf{u}_i\in\mathbb{R}^n$$

  $$\rightarrow \mathbf{u}_i{}^T\mathbf{M}_\mathrm{T}\,\mathbf{u}_i\,\ddot{q}_i(t)+\mathbf{u}_i{}^T\mathbf{D}_\mathrm{T}\,\mathbf{u}_i\,\dot{q}_i(t)+\mathbf{u}_i{}^T\mathbf{K}_\mathrm{T}\,\mathbf{u}_i\,q_i(t)=\mathbf{u}_i{}^T\mathbf{h}_\mathrm{T}(t)$$

  No complete diagonalization!

- 2nd possibility: *Complex eigenvectors*

  $$\mathbf{M}_\mathrm{T}\,\ddot{\mathbf{y}}_\mathrm{T}(t)+\mathbf{D}_\mathrm{T}\,\dot{\mathbf{y}}_\mathrm{T}(t)+\mathbf{K}_\mathrm{T}\,\mathbf{y}_\mathrm{T}(t)=\mathbf{h}_\mathrm{T}(t)\Rightarrow\dot{\mathbf{z}}(t)=\mathbf{A}\,\mathbf{z}(t)+\mathbf{b}(t)$$

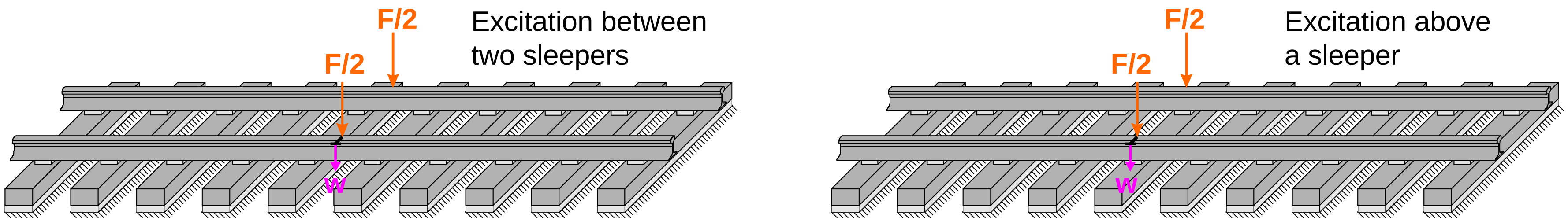
  Left EV: $\mathbf{v}_i{}^H\mathbf{A}=\lambda_i\mathbf{v}_i{}^H,\ \mathbf{v}_i\in\mathbb{C}^{2n}$

  Right EV: $\mathbf{A}\,\mathbf{w}_i=\lambda_i\,\mathbf{w}_i\ ,\mathbf{w}_i\in\mathbb{C}^{2n}$

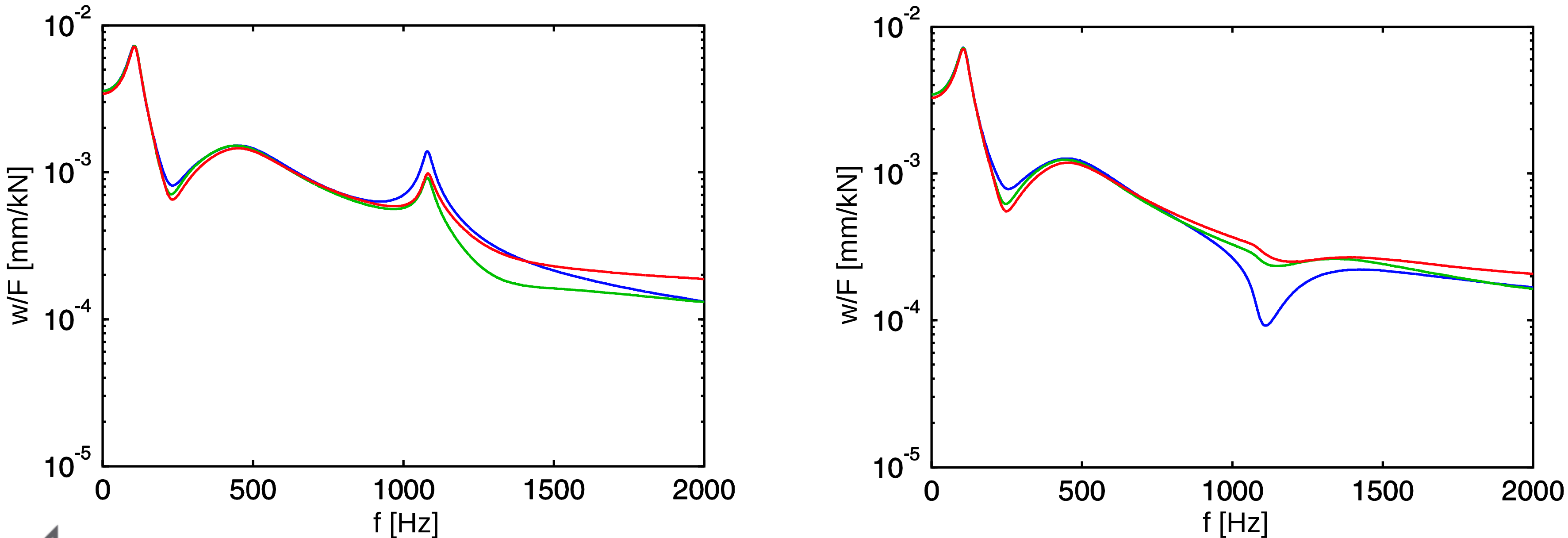
  → Decoupled equations: $\dot{q}_i(t)=\lambda_i\,q_i(t)+\mathbf{v}_i{}^H\mathbf{b}(t)$

  Modal synthesis: $\mathbf{z}(t)=\sum_{i=1}^{2n}\mathbf{w}_i\,q_i(t)$

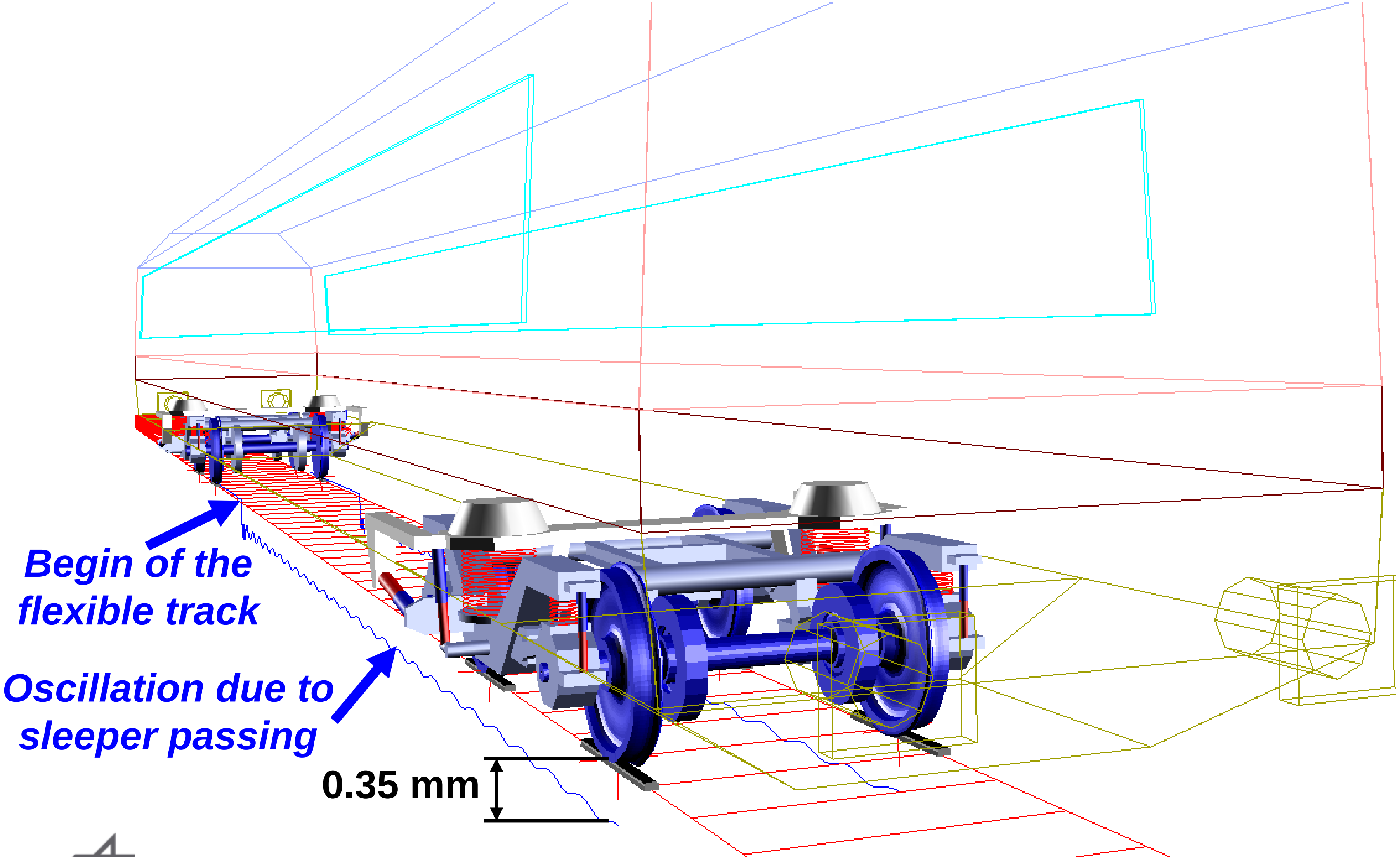
Influence of the modal description: Vertical receptance



Complex EVs (original system) 128 sleepers | **Real EVs (all EVs) 128 sleepers** | **Selected real EVs 128 sleepers**



Interaction of flexible wheelsets and flexible track



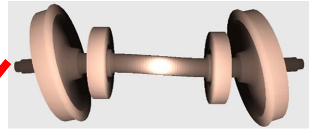
Conclusion

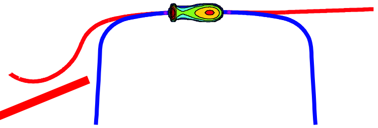
- Including the *structural dynamics* of *wheelsets* and *track* require special approaches because of *moving loads*
- Flexible wheelset
  - Exploiting the characteristics of a rotational symmetric structure
  - Semi-analytic solution: Trigonometric function with one periodicity
- Flexible track
  - Structural dynamics model of the track with discrete sleepers
  - Ring-shaped track model → separation from track topology
  - Integration by co-simulation
- Successful implementation in a DLR SIMPACK-8.901-developer version (without any restrictions for the user)
- ***Enhancing the modeling of a system requires similar detailing of the subsystems***

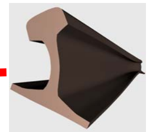
Conclusion (2)

Enhanced modeling for extended frequency range


Source: www.railfaneurope.net







- Flexible rotating wheelset — implemented
- Non-elliptic contact — **next step …**
- Flexible rail — implemented

Applications

- acoustics
- strength calculation of wheelset axle, wheel disc and track components
- dynamic effects causing
  - traction control problems
  - non uniform wear (corrugation)