

Self-excited vibrations of magnetic track brakes

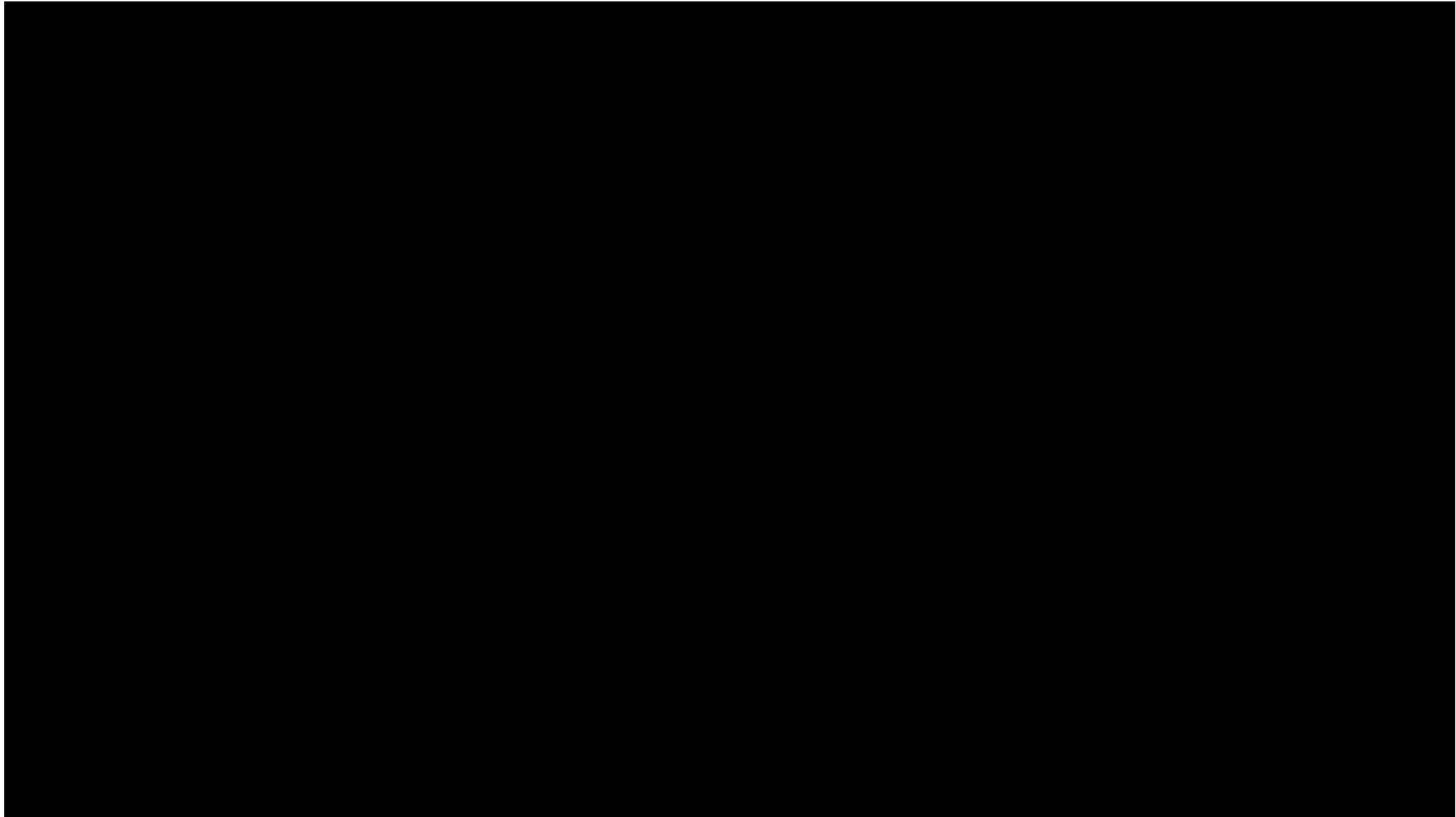
Modelling, analysis and mitigation

ECS Simulation Conference

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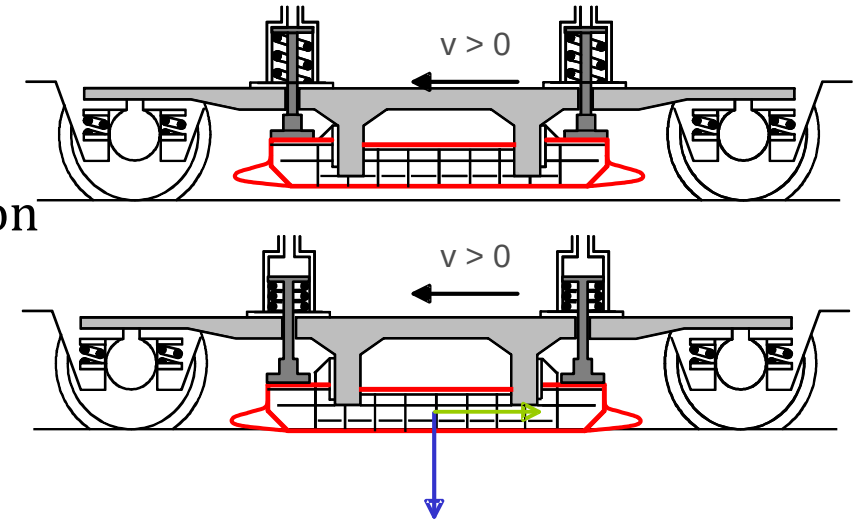
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Increase of braking performance:

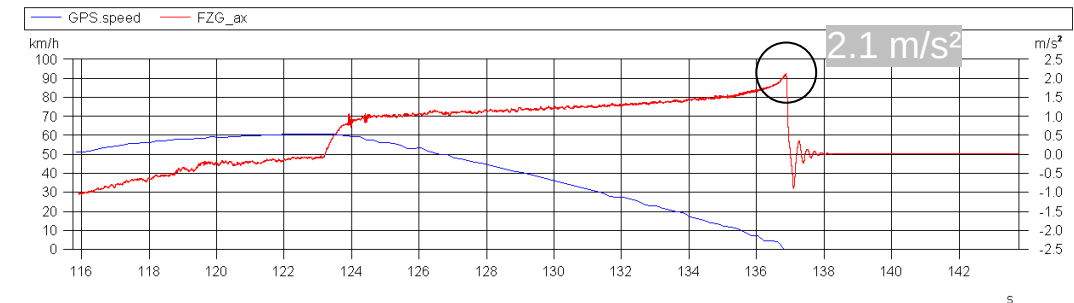
- Independent of wheel/rail adhesion
- Conditioning of the rail head improves the wheel/rail adhesion
- Higher allowable speeds at given signal distances
- Improvements in low adhesion conditions (autumn, foliage, contaminated rails)



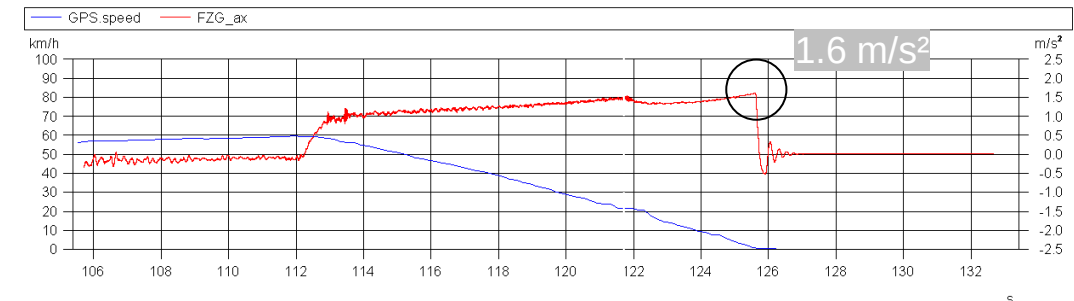
Track brakes and low velocities

- Common practice: deactivation at < 20 km/h
- Decelerations increase at low velocities
- Avoid stopping jerks and peak decelerations
- However: demands on brake performance require activation until full stop

Test 1: Active until full stop

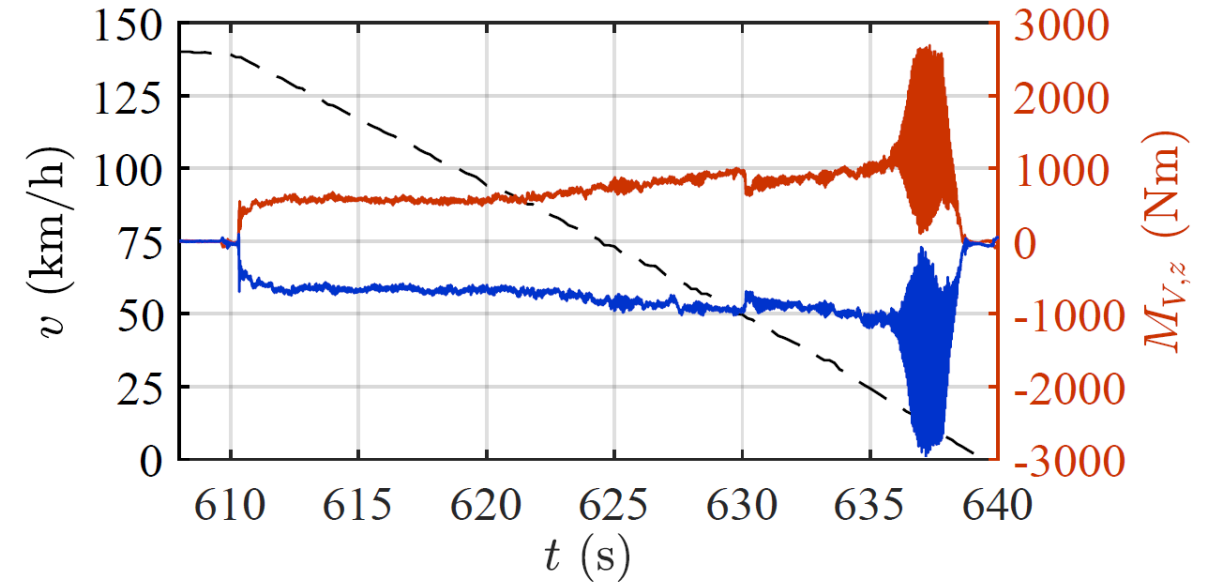
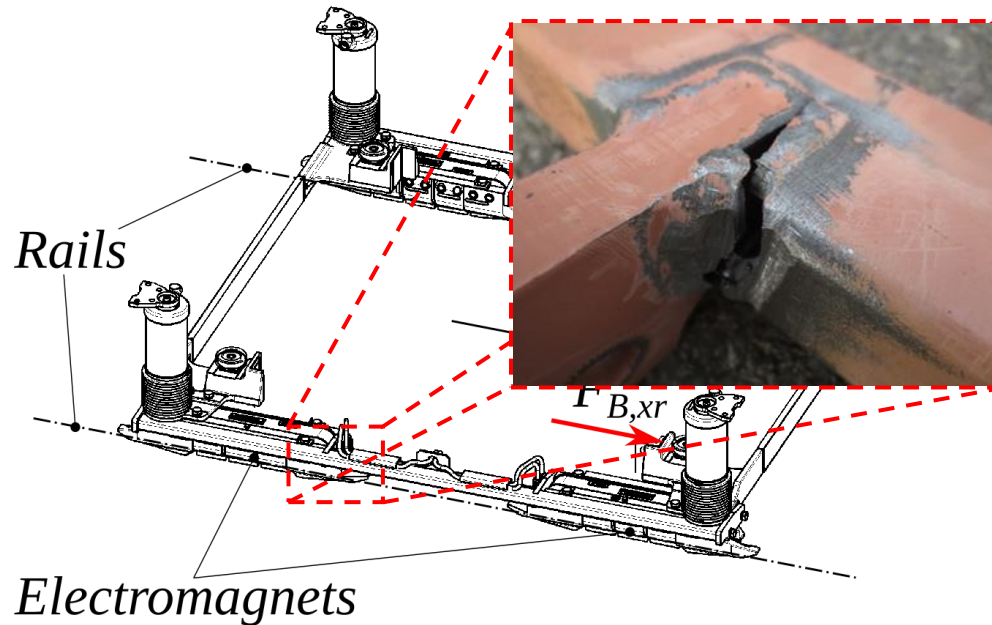


Test 2: Deactivation at 25 km/h



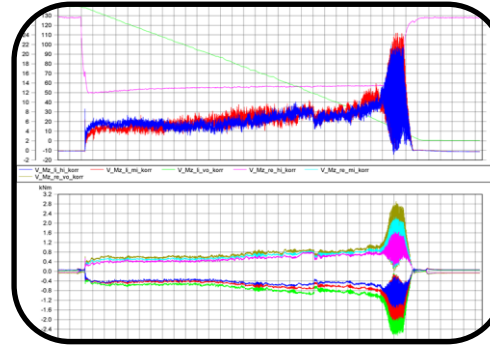
Field tests in low-speed application show challenges when approaching low velocities

- Severe vibrations may occur
- Reduction of brake performance
- Noise
- High fatigue loads and damage

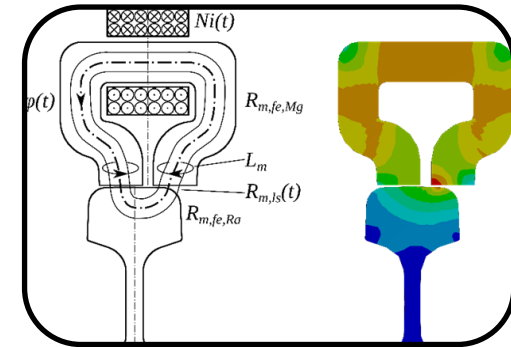




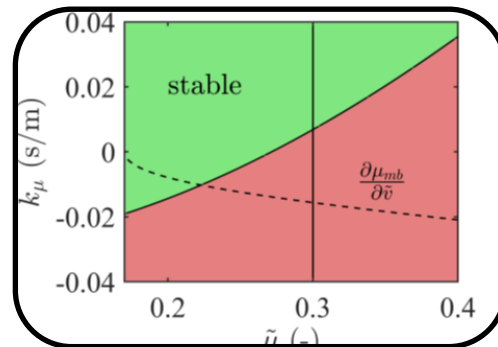
Motivation



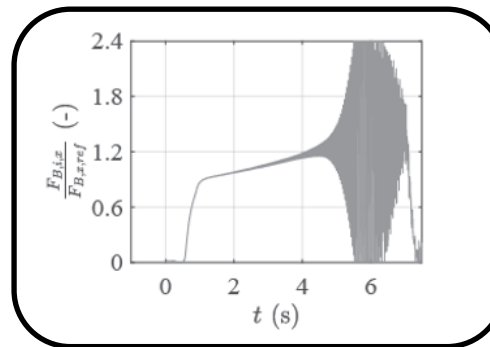
Analysis of field tests



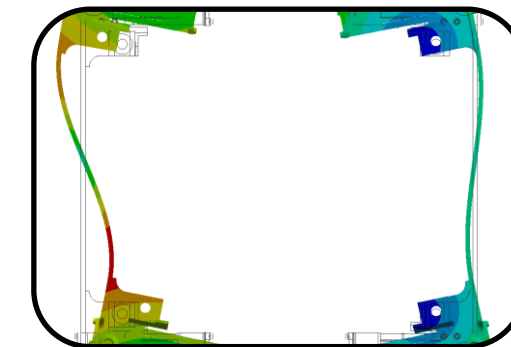
Modelling



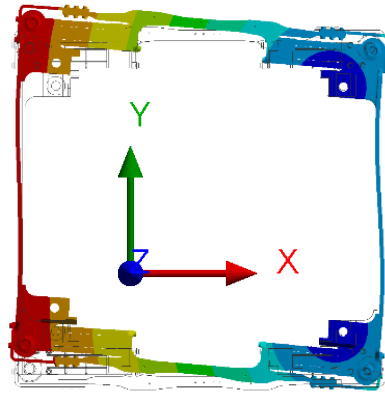
Stability analysis



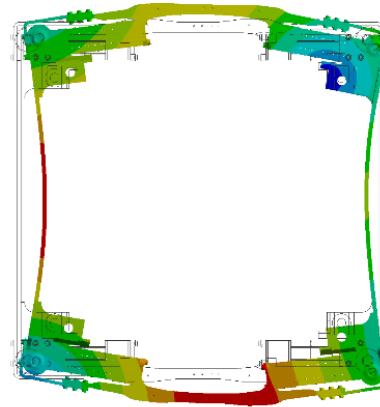
Mitigation



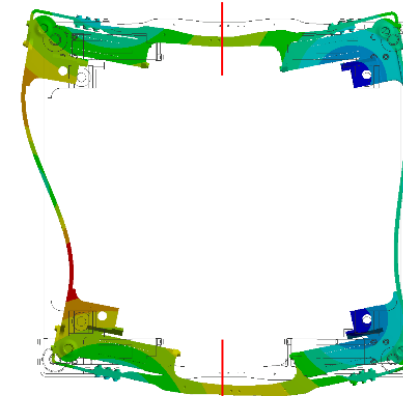
Conclusions/Outlook



1st asym. mode ≈ 8 Hz



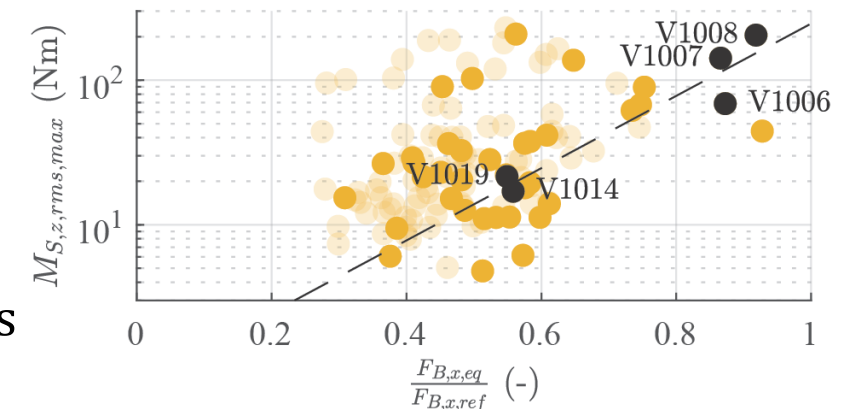
1st sym. mode ≈ 16 Hz



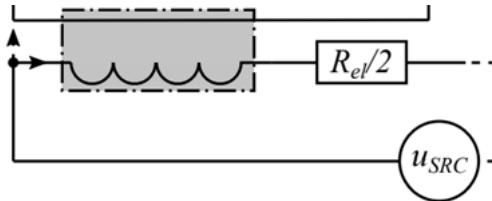
2nd asym. mode ≈ 28 Hz

Field measurements during braking tests

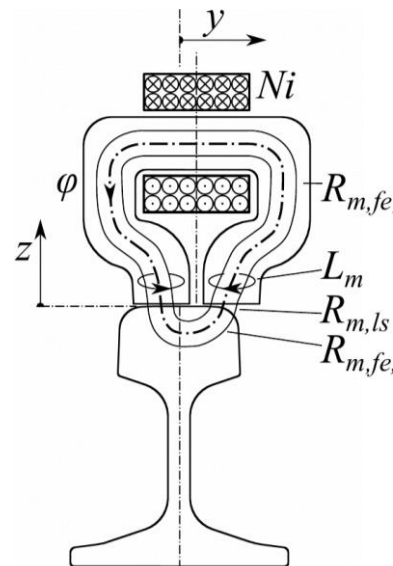
- Measurement of **bending moments** M_z using strain-gages
- Vibration corresponds to 2nd asymmetric structural mode
- Vibrations occur below 20 km/h
- Friction measurements show increase at low sliding velocities



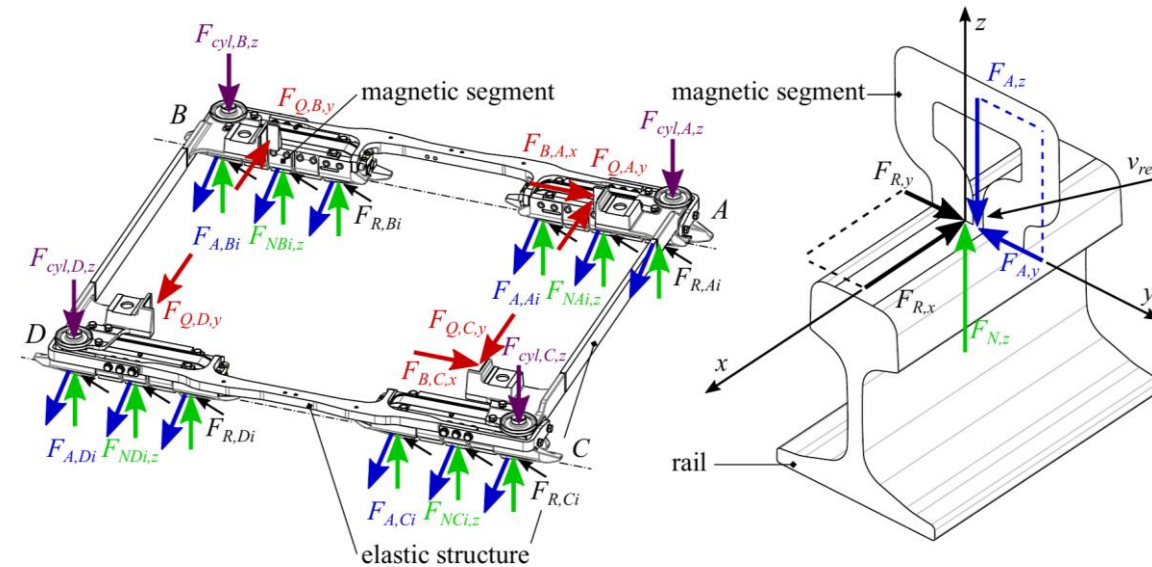
Electric domain



Magnetic domain

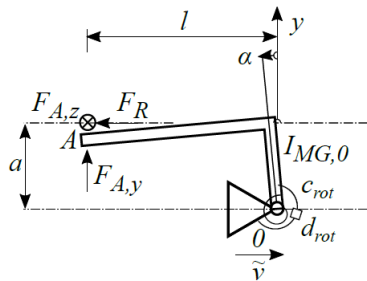


Mechanical domain



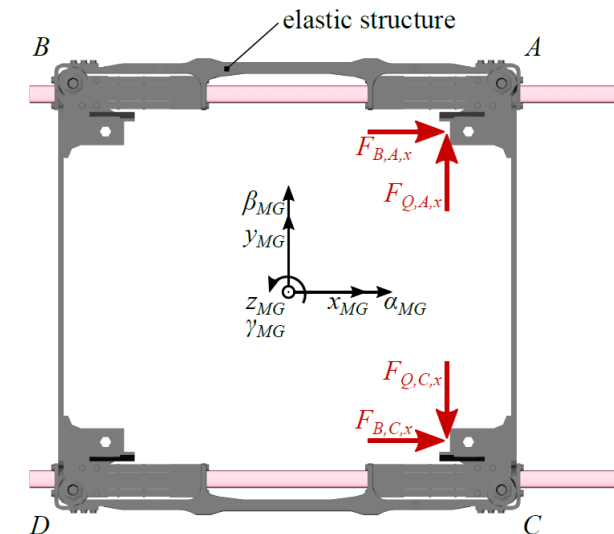
Single-magnet model

- Minimal model to study basic self-excitation mechanisms
- Quarter-model
- Single magnetic circuit
- Linear analysis
- 1.5 DoF



Multibody dynamics model

- Velocity dependent effects
- Contact parameters rail/magnet
- Electrical connection
- Qualitatively comparable with field tests
- Operational conditions



————— level of detail —————→

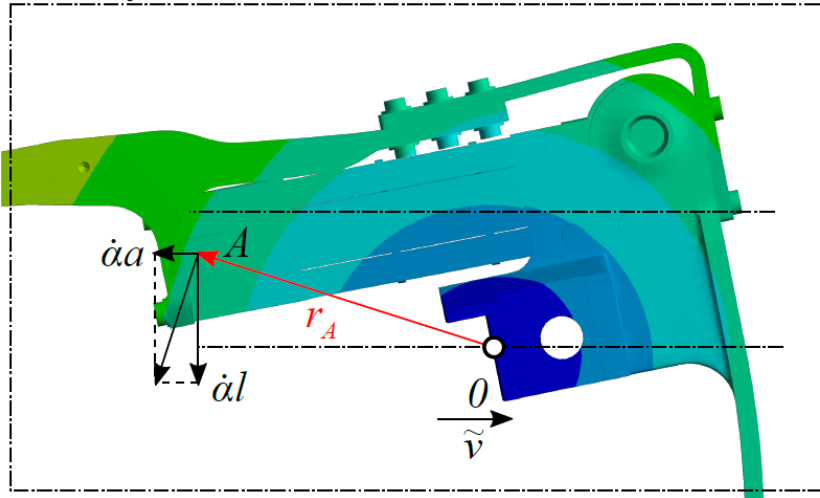
A simplified mechanical 1-DoF model is used to study basic phenomena

- Parameterization of spring stiffness and mass to match 2nd asymmetric mode
- Magnetic forces and friction forces vary with magnetic flux and lateral displacement
- Friction characteristics with negative slope w.r.t. sliding velocity may lead to self-excitation

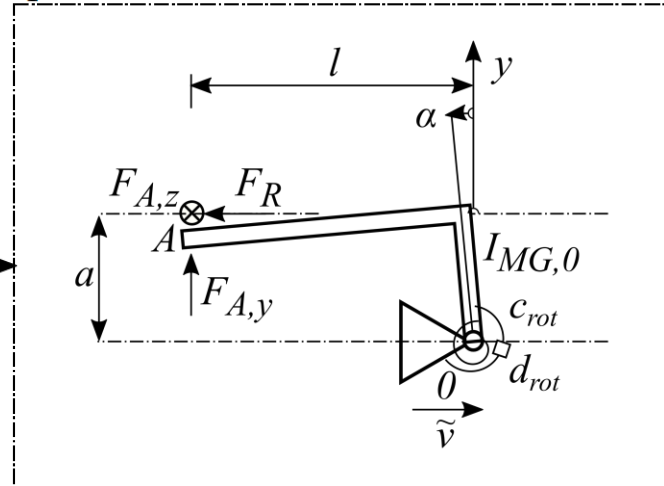
$$I_{MG,0}\ddot{\alpha} + d_{rot}\dot{\alpha} + c_{rot}\alpha = aF_{A,z}(\tilde{\mu}_G - k_{\mu}a\dot{\alpha}) - lF_{A,y}$$

$$\mu_G(v_{rel}) = \tilde{\mu}_G + k_{\mu}v_{rel}$$

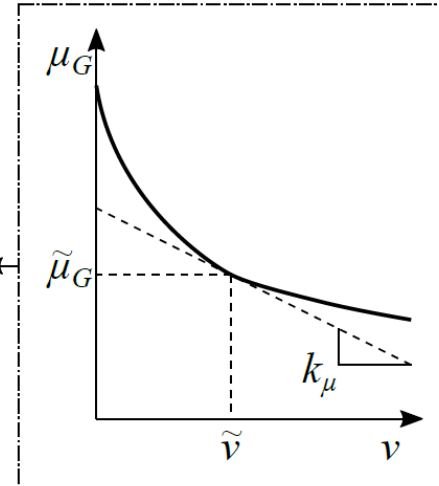
2nd asymmetric mode



quarter model



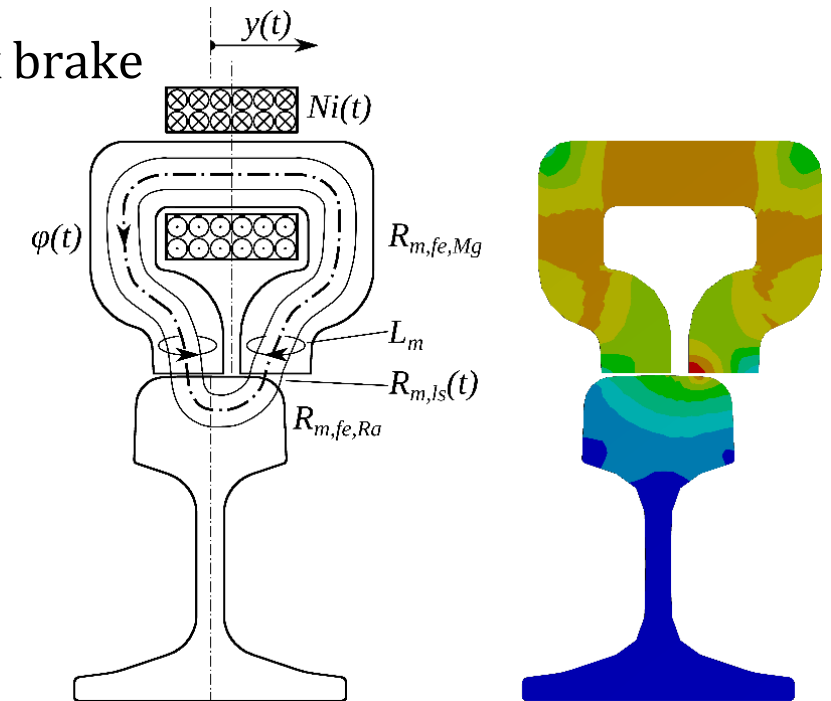
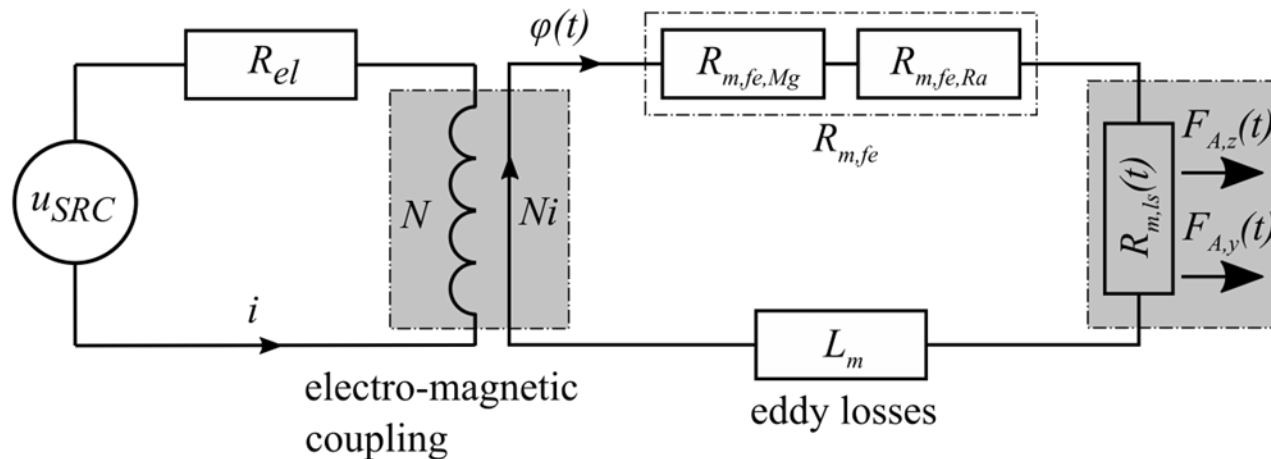
friction characteristics



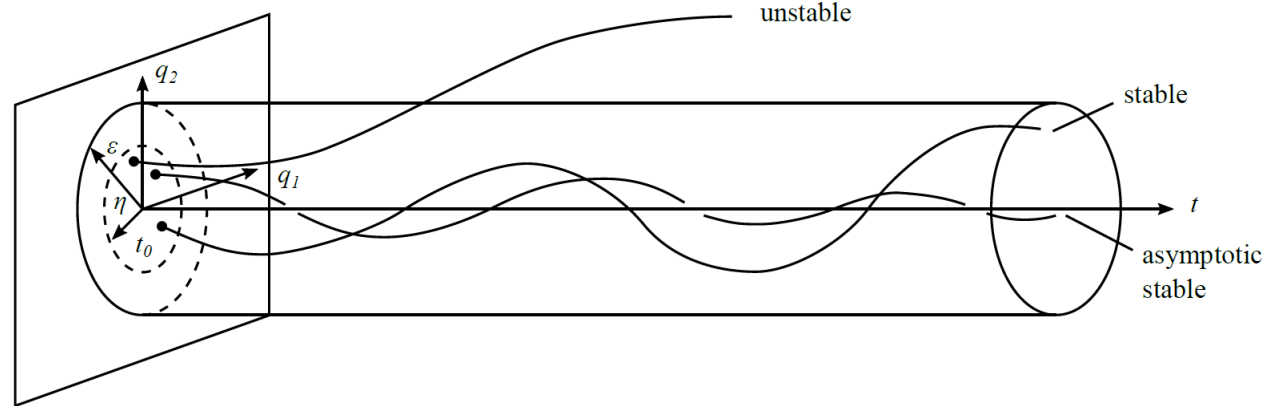
Coupled electric circuit and magnetic circuit

Magnetic flux and magnetic forces vary with lateral displacement

- Finite element model to calculate the magnetic circuit
- The magnetic circuit is approximated by a network of reluctances and eddy-current losses
- Static reluctances: iron-core
- Variable reluctance: effective air-gap
- Effective air-gap depends on relative position of rail and track brake



Stability



Linear(-ised) system: $\dot{x} = \mathbf{A}_{sys}x$

Char. polynomial: $p(\lambda) = \det(\mathbf{A}_{sys} - \lambda \mathbf{I}) = \lambda^n + a_1 \lambda^{n-1} + a_2 \lambda^{n-2} + \dots + a_{n-1} \lambda + a_n$

Asymptotic stability: $\text{Re}(\lambda) < 0$

Hurwitz Criterion:

$$\mathbf{H} = \begin{bmatrix} a_1 & 1 & 0 & \dots & 0 \\ a_3 & a_2 & a_1 & \dots & \vdots \\ a_5 & a_4 & a_3 & \dots & \vdots \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & \dots & \dots & a_n \end{bmatrix}$$

$H_i > 0$, with

$$H_1 = a_1, H_2 = \det \begin{bmatrix} a_1 & 1 \\ a_3 & a_2 \end{bmatrix}, \dots, H_n = \det \mathbf{H}$$

Linearised system:

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 \\ -a_{21} & -a_{22} & -a_{23} \\ -a_{31} & 0 & -a_{33} \end{bmatrix}, \mathbf{b} = \begin{bmatrix} 0 \\ 0 \\ b_3 \end{bmatrix}$$

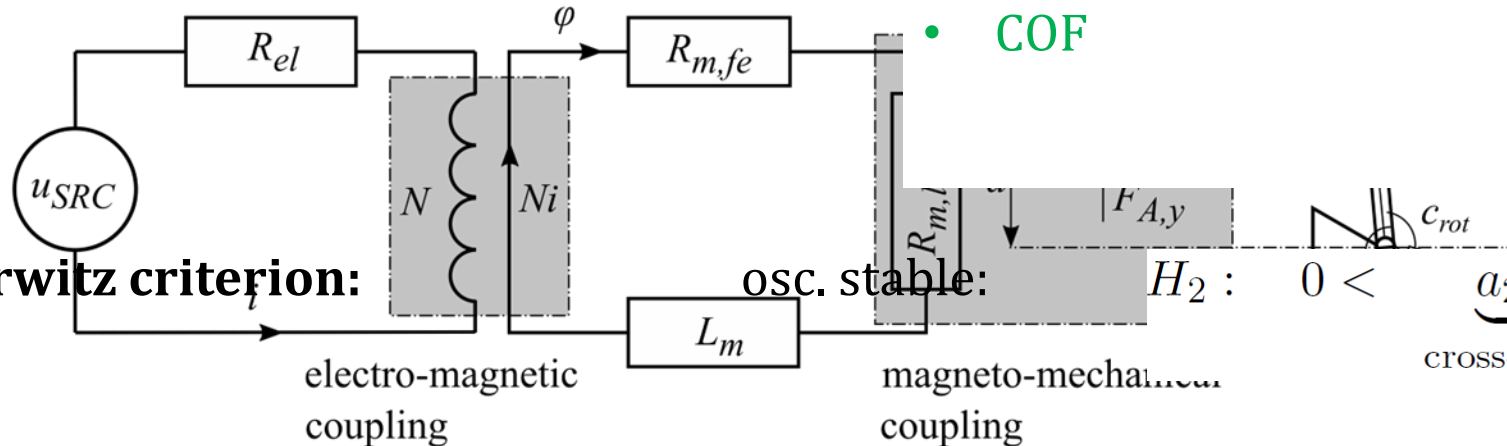
$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{b}u$$

$$\mathbf{x} = [\Delta\alpha \ \Delta\dot{\alpha} \ \Delta\phi]^T$$

linear „1.5-DoF“ system:

Hurwitz criterion:

osc. stable:



Damping term < 0 if:

Gradient of the COF w.r.t. the sliding velocity < 0

damping term:

$$a_{22} =$$

$$\frac{d_{rot} + \frac{\tilde{\phi}^2 a^2 k_{\mu}}{\mu_0 A}}{I_{MG,0}} \leq 0$$

cross-coupling term:

$$a_{23} =$$

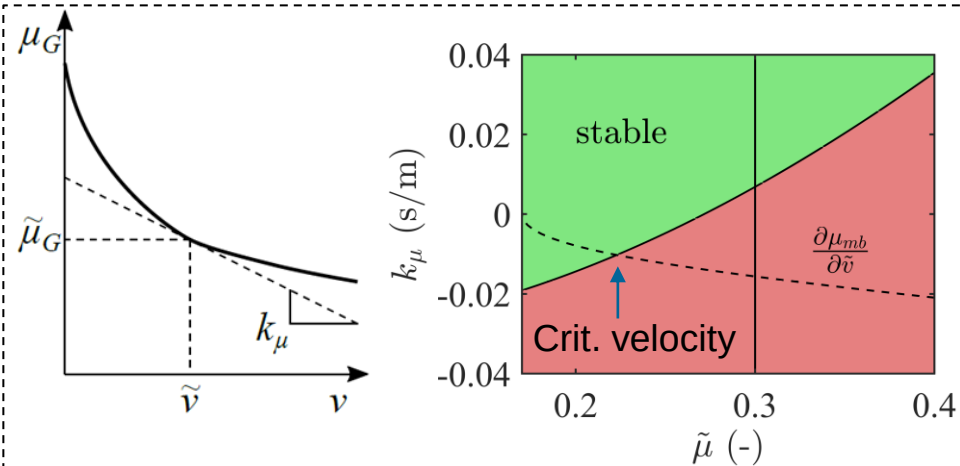
$$\frac{\frac{\tilde{\phi}}{\mu_0 A} \left(\frac{\partial s}{\partial \alpha} \Big|_0 - 2a\tilde{\mu}_G \right)}{I_{MG,0}} \leq 0$$

Cross-coupling term < 0 dependent on:

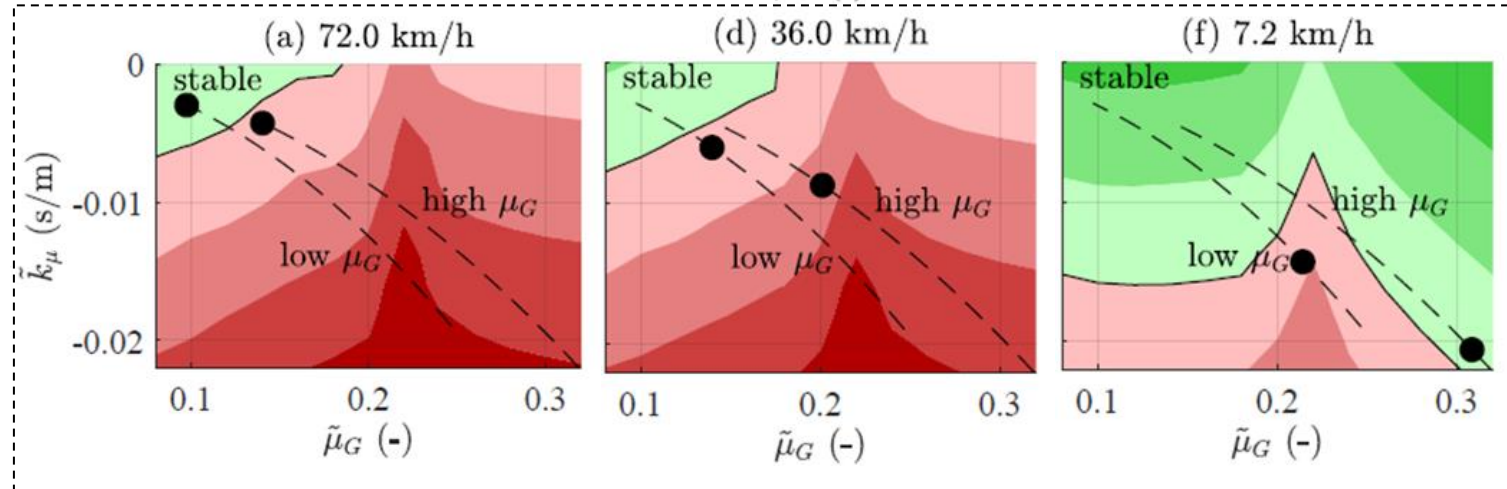
- Steady state values
- Geometry
- COF

$$0 < \underbrace{a_{23}a_{31}}_{\text{cross-coupling}} + \underbrace{a_{22}}_{\text{damping}} (a_{21} + a_{22}a_{33} + a_{33}^2)$$

Linear model



MBD model



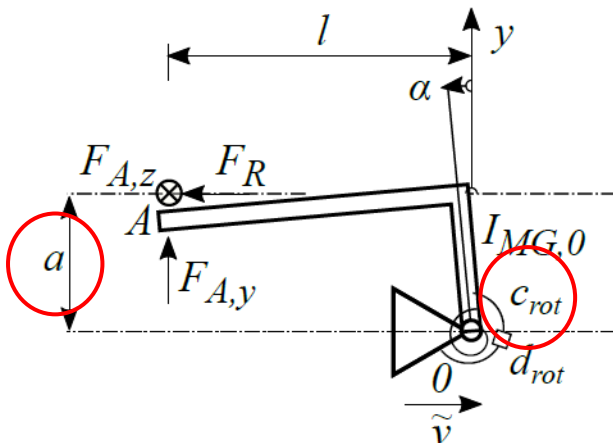
- Stability varies with slope of friction coefficient **and** static friction coefficient
- Velocity dependent friction characteristics cross stability border
- MBD: Stable area increases with decreasing sliding velocity (lateral friction)
- Good qualitative agreement of linear model and MBD model for COF < 0.22

$$a_{22} = \frac{d_{rot} + \frac{\tilde{\phi}^2 a^2 k_\mu}{\mu_0 A}}{I_{MG,0}} \leq 0$$

$$a_{23} = \frac{\frac{\tilde{\phi}}{\mu_0 A} \left(\frac{\partial s}{\partial \alpha} \Big|_0 - 2a \tilde{\mu}_G \right)}{I_{MG,0}} \leq 0$$

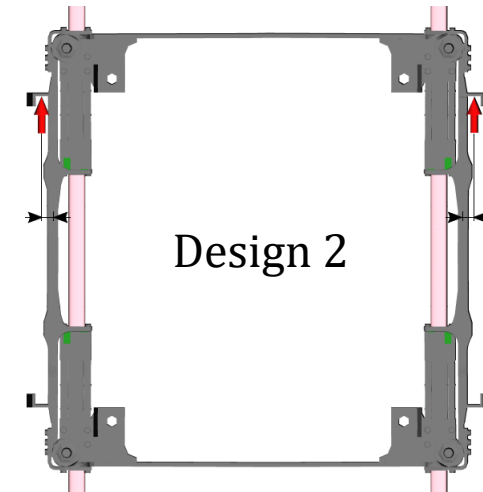
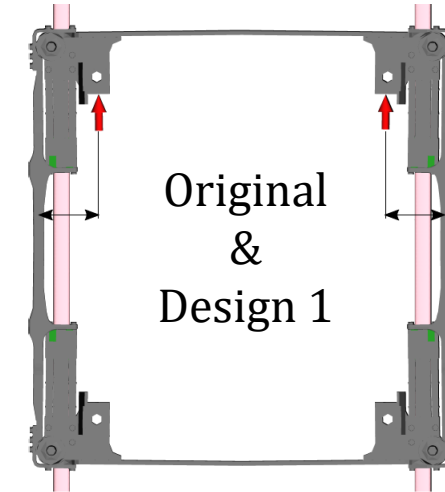
Mitigation by decreasing cross-coupling terms

- Design 1: increased stiffness
- Design 2: decreased lateral distance of the transmission link
- Design 3: interchanged electrical connection (not in presentation)

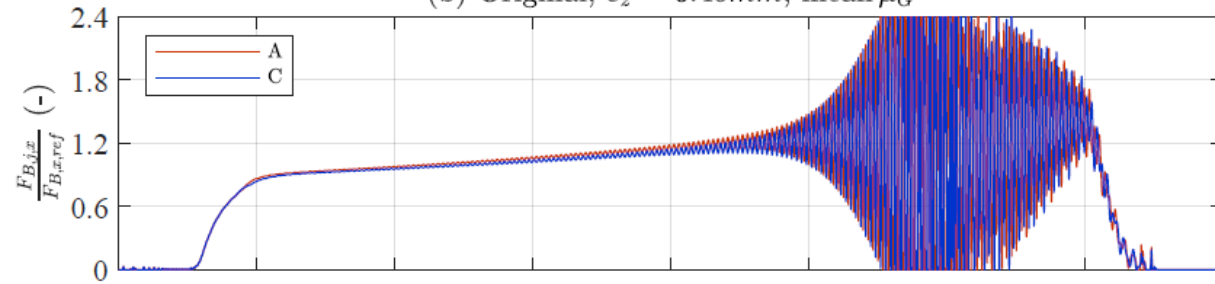


$$a_{23} =$$

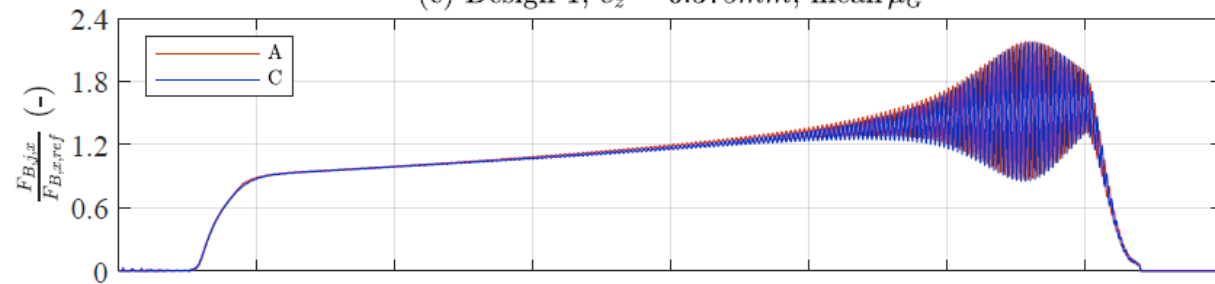
$$\frac{\frac{\tilde{\phi}}{\mu_0 A} \left(\frac{\partial s}{\partial \alpha} \Big|_0 - 2a\tilde{\mu}_G \right)}{I_{MG,0}} \lesseqgtr 0$$



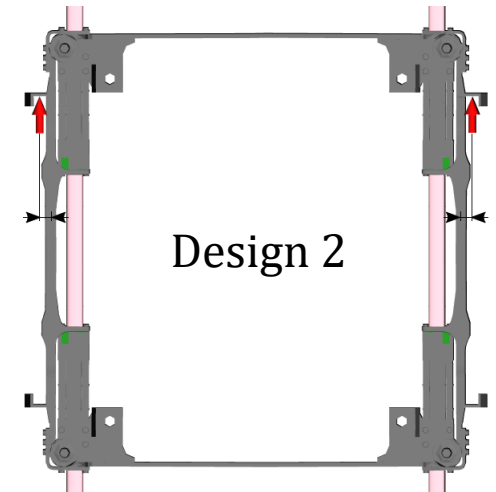
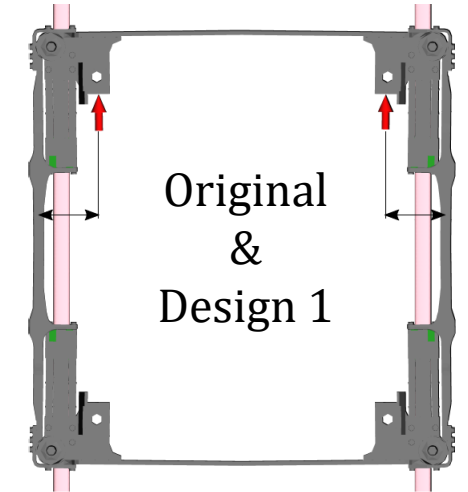
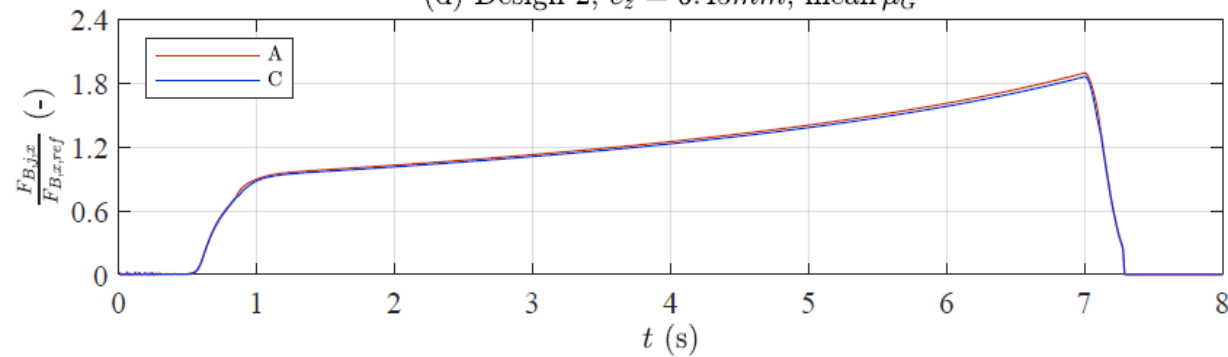
(b) Original, $e_z = 0.45mm$, mean μ_G



(c) Design 1, $e_z = 0.375mm$, mean μ_G



(d) Design 2, $e_z = 0.45mm$, mean μ_G

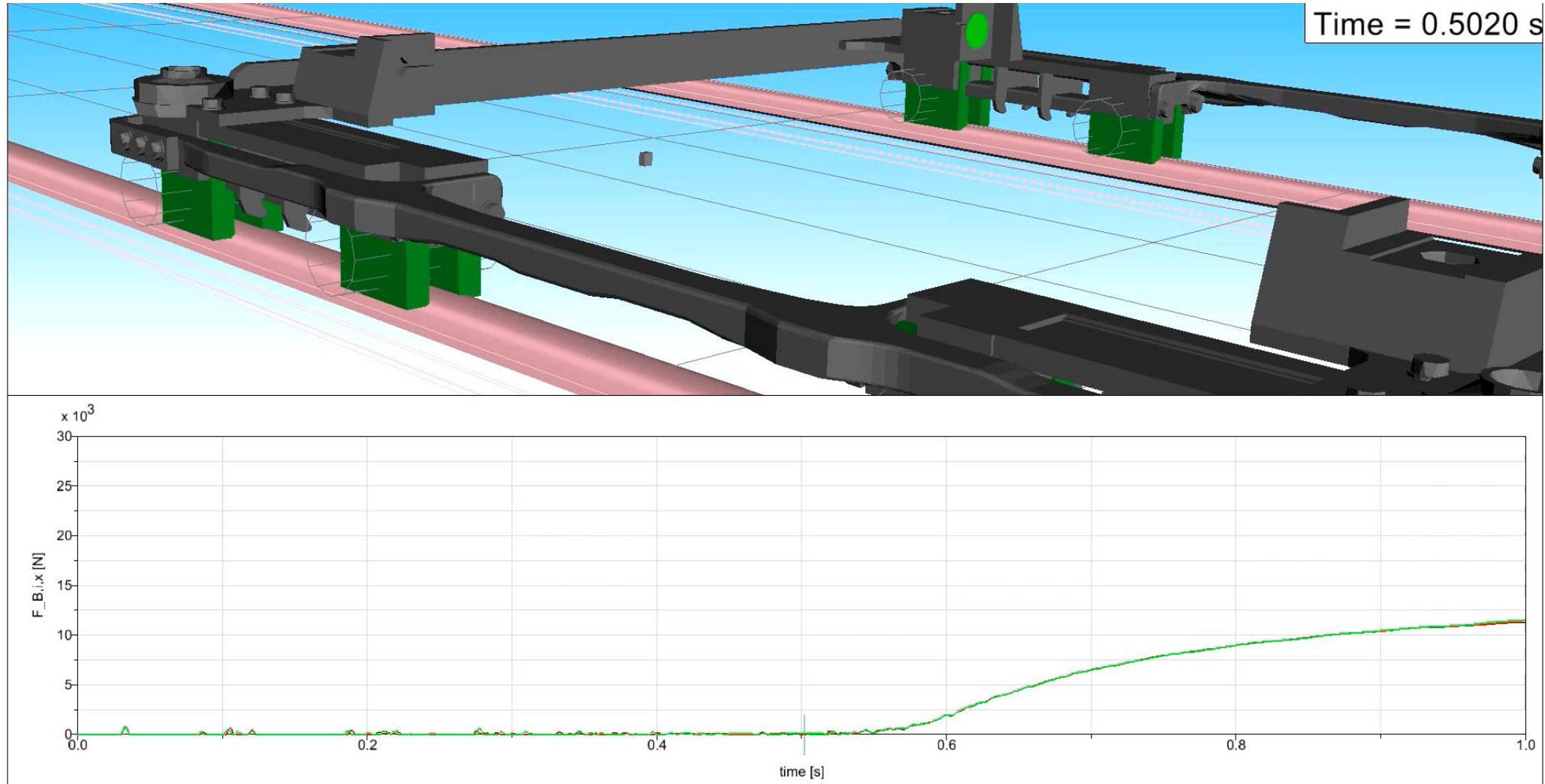


- **Two mechanisms for self-excited vibrations** of magnetic track brakes have been identified
- Friction vibrations caused by a **negative slope of the friction characteristics** w.r.t. the sliding velocity
- **Electro-magnetic and mechanical coupling** of first order and second order differential equations
- Stability depends on operational and environmental parameters
- System can be stabilised by modifying the design of the track brake

Not in presentation:

- Kinetic energy of the train provides the source to maintain self-excited vibrations
- Electro-magnetic coupling is amplified for electrical in-series connection of the magnets and asymmetric modes

- **Active mitigation:** anti-vibration controller using voltage/current or pressure
- **Stability analysis:** Non-linear methods including bifurcation analysis; stable limit cycles
- **Modelling of contact/friction:** 3D-pole shoe/rail contact; third-body layer
- **Modelling of magnetism:** non-linear magnetisation, hysteretic and velocity-dependent effects
- Continuing research is highly recommended and eagerly anticipated



DISCUSSION

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