Technische Universität Wien

SIEMENS

Simulation of an Active Vibration Control for Flexible Railway Car Bodies

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Motivation

- Low vibration level crucial for good ride comfort
- Maximum human vibration responsiveness between 4 and 8 Hz (e. g. ISO 2631)
- Low damped eigenfrequencies of lightweight car bodies near this region
- Great influence of car body structural flexibility

Motivation

- Conventional solution: Stiffening of car body structure to increase eigenfrequency
- Stiffening of structure increases weight
- New solution: Active vibration control
- Actuators and sensors connected via a control loop change the car body frequency response

Introduction and Overview

- **Integration of elastic bodies in SIMPACK by modal transformation of FE-data**
- **Deformation** $\mathbf{u}(\mathbf{R},t) = \boldsymbol{\Phi}(\mathbf{R})\mathbf{q}(t)$

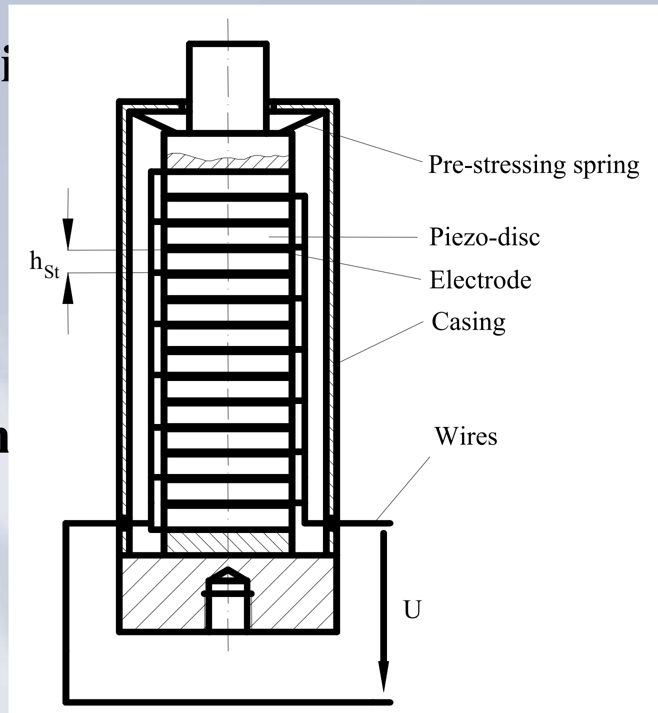
  $\boldsymbol{\Phi}(\mathbf{R})$ **eigenmodes,** $\mathbf{q}(t)$ **modal coordinates**
- **Modal mass matrix** $\mathbf{M}_{ee} = \boldsymbol{\Phi}^T \mathbf{M} \boldsymbol{\Phi}$
- **Modal stiffness matrix** $\mathbf{K}_{ee} = \boldsymbol{\Phi}^T \mathbf{K} \boldsymbol{\Phi}$

Introduction and Overview

- Active vibration control
- Using actuators and a control loop to increase damping of selected eigenmodes
- Actuator/Sensor: piezoceramics

Piezo actuators and sensors

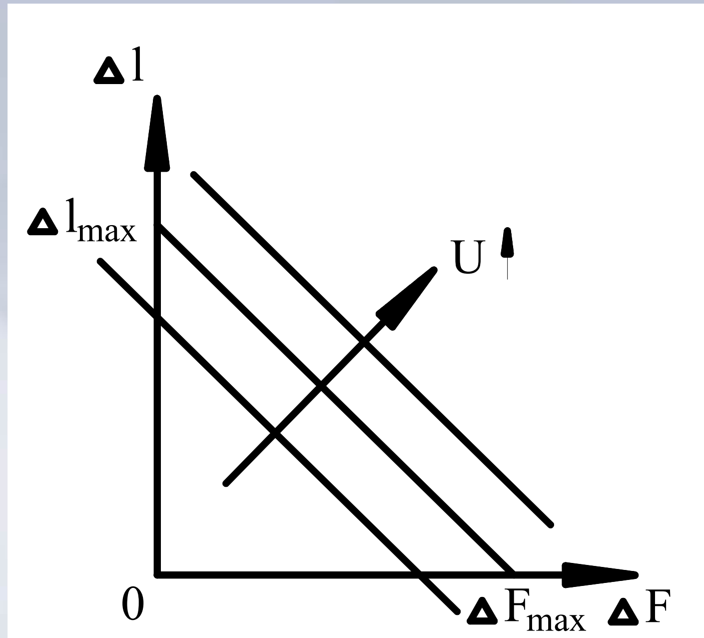
- Actuator: applied voltage – strain or appli
  voltage - Force
- Sensor: Strain – electr. charge or
  strain - voltage
- Maximum stroke up to about 100 µm usin
  stack actuators
- Maximum forces up to $10^5\ N$



Stack actuator

Piezo actuators and sensors

- Actuator force proportional to applied voltage at stroke=0
- Actuator force depends on stroke



Controller Design

- Differential equation of the flexible body with actuators

$$\mathbf{M}_{ee}\ddot{\mathbf{q}} + \mathbf{D}_{ee}\dot{\mathbf{q}} + \mathbf{K}_{ee}\mathbf{q} = -\mathbf{K}_{e\varphi}\mathbf{u}_{\varphi}$$

- Sensor equation

$$\mathbf{Q}_{\varphi} = \mathbf{K}_{e\varphi}^{T}\mathbf{q}\left(+\mathbf{K}_{\varphi\varphi}\mathbf{u}_{\varphi}\right)$$

- Obtain linear state-space model:

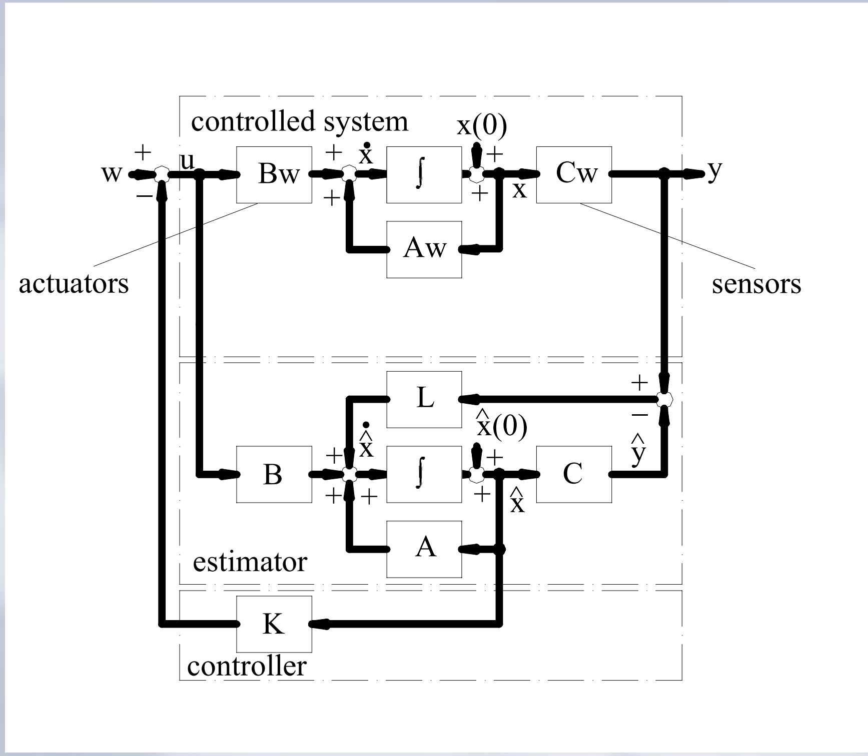
$$\mathbf{x} = \begin{pmatrix}\mathbf{q} & \dot{\mathbf{q}}\end{pmatrix}^{T}$$

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \qquad \mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}$$

- LQ-state observer to reconstruct an estimate of the state vector

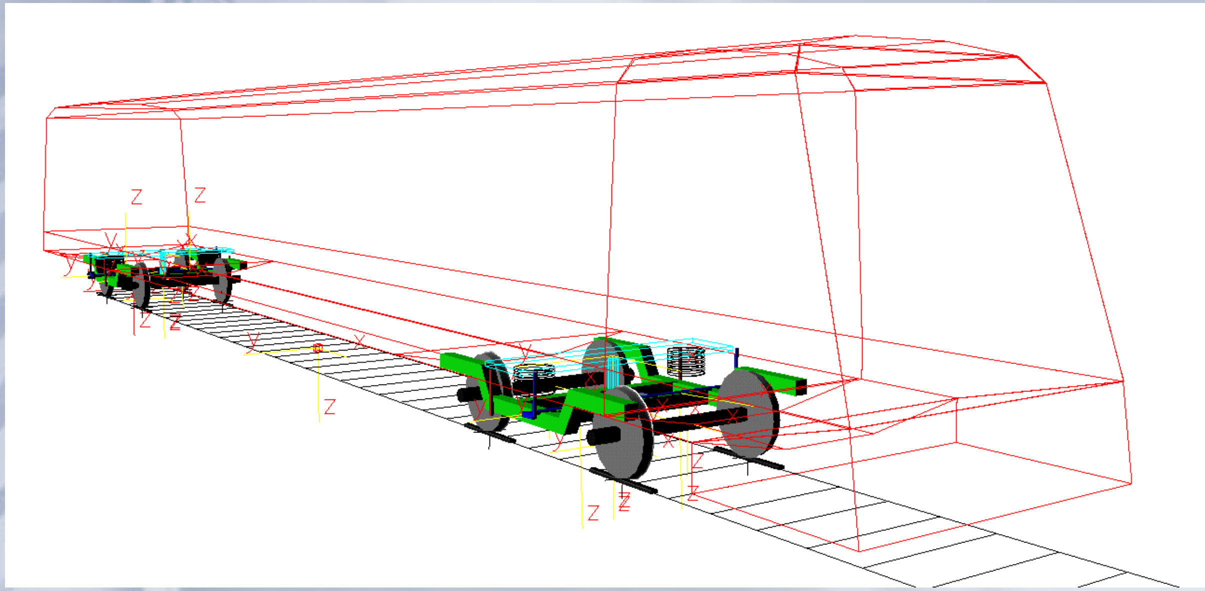
Controller Design

- Pole placement using state feedback
- Increase damping for controlled modes from 2% to 30%



Co-Simulation using SIMPACK/Simulink

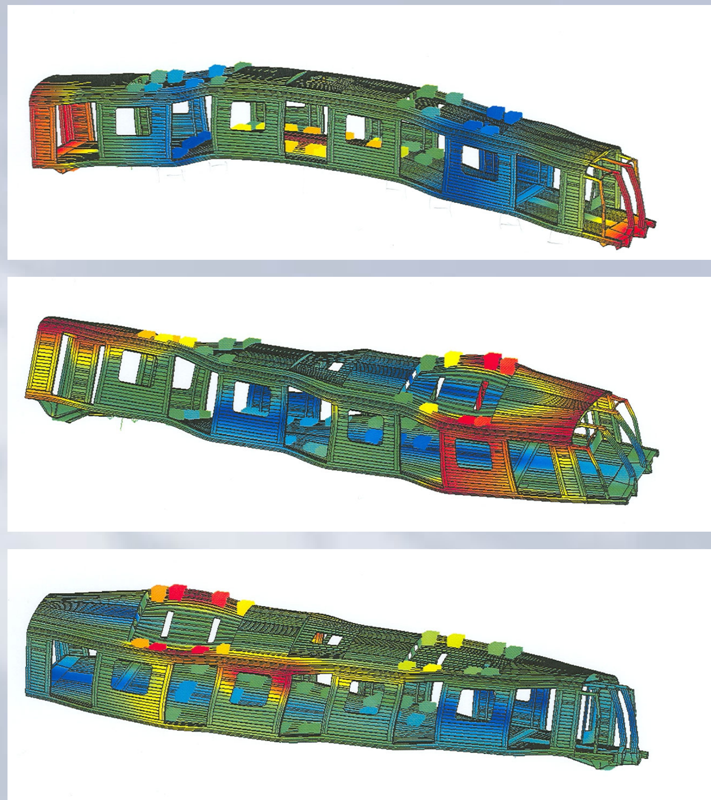
- SIMPACK model of a metro vehicle with flexible car body
- Flexibility of car body described by 17 Eigenmodes



Co-Simulation using SIMPACK/Simulink

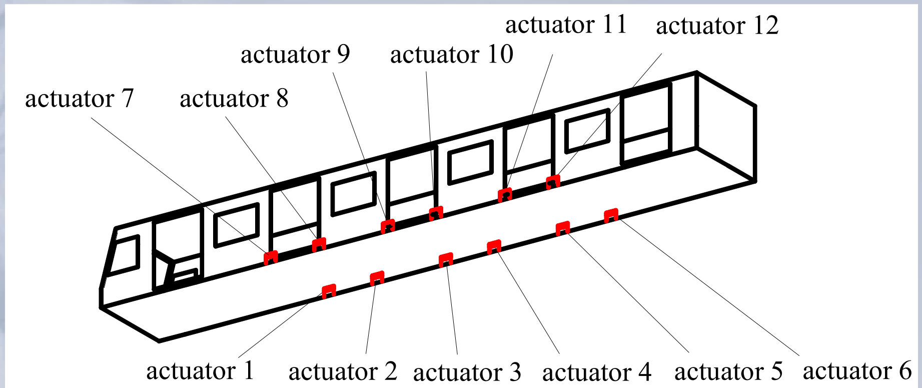
- Active vibration control – damping of
  - 1st vertical bending mode
  - 1st torsion mode and
  - 1st diagonal distorsion

  increased to 30 %



Co-Simulation using SIMPACK/Simulink

- Placing of 12 actuators



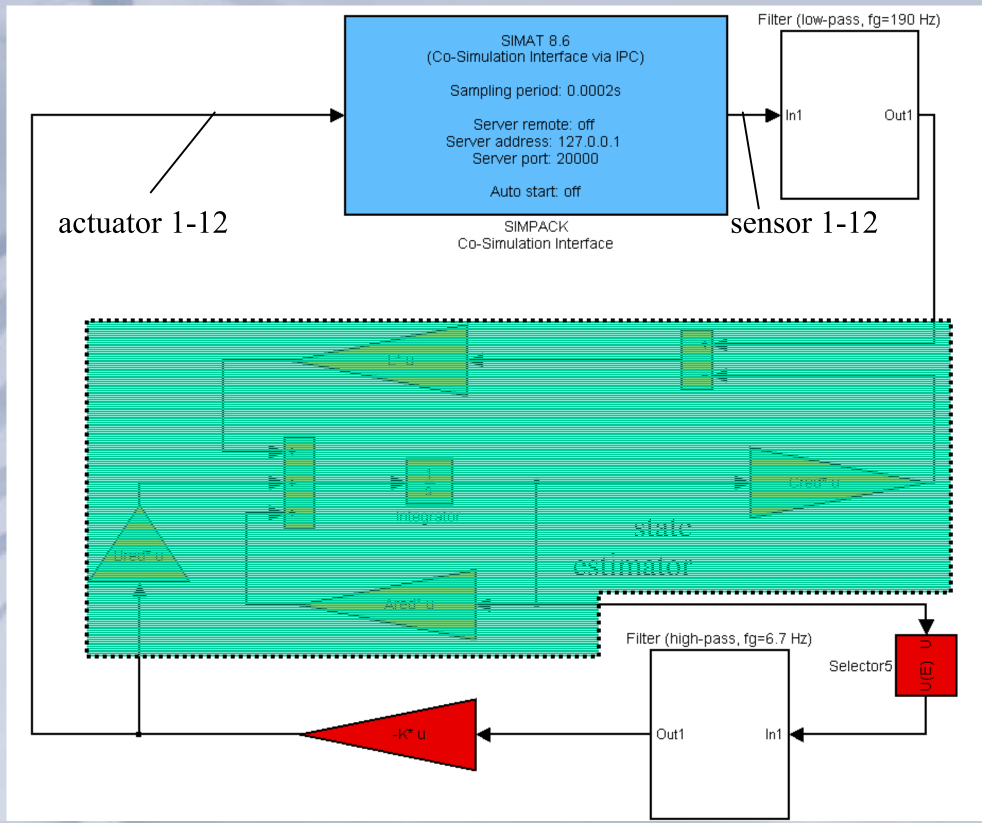
- Calculation of 12 additional Frequency Response Modes
- Total of 29 shape functions for flexible car body
- Adding spring-damper elements at actuator positions to include actuator stiffness
- Placing 12 sensors at actuator positions

Co-Simulation using SIMPACK/Simulink

- Observer-based state feedback controller
- High-pass filter for static deformation
- Low-pass filter to reduce sensor noise
- Controller realized using Matlab/Simulink

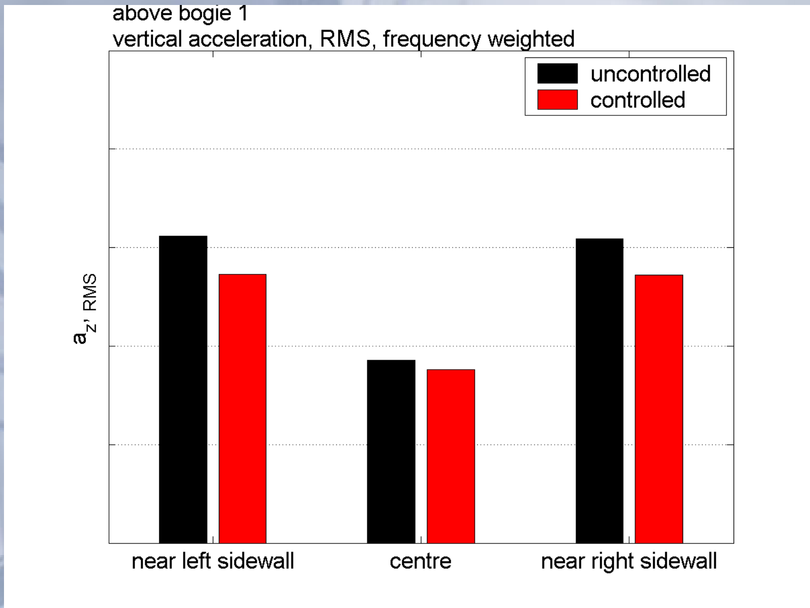
Co-Simulation using SIMPACK/Simulink

- Observer based controller in Matlab/Simulink

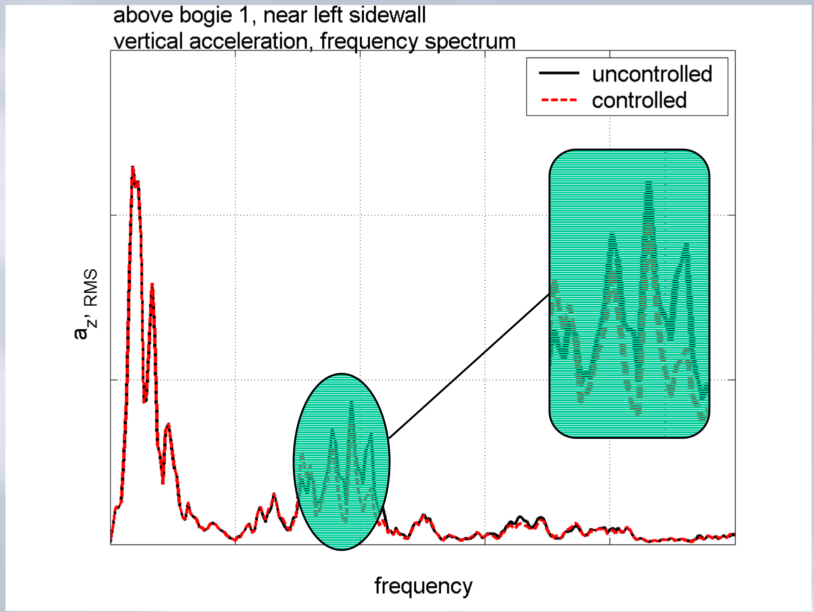


Simulation Results

Ride comfort on a straight track with irregularities DB High (considered period t=36s, s=800m, v=22m/s)



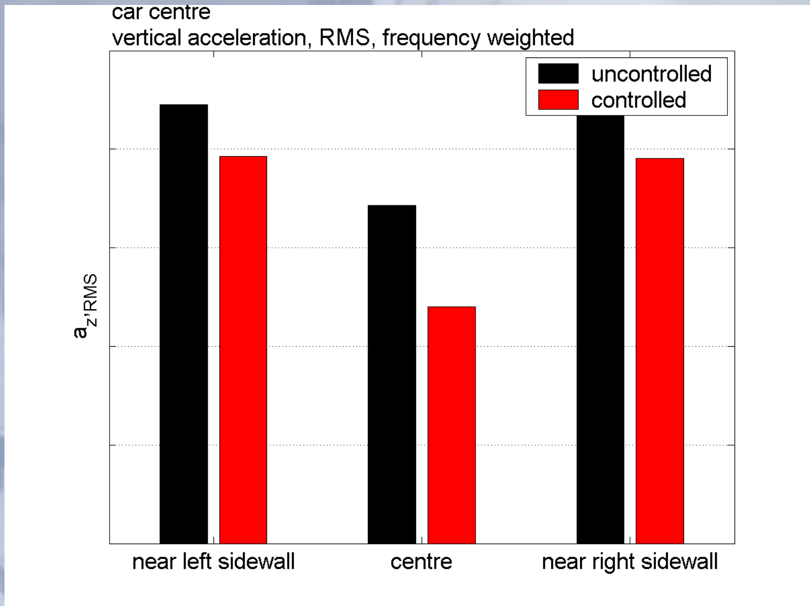
Vertical acceleration above bogie 1
ISO 2631 weighted RMS



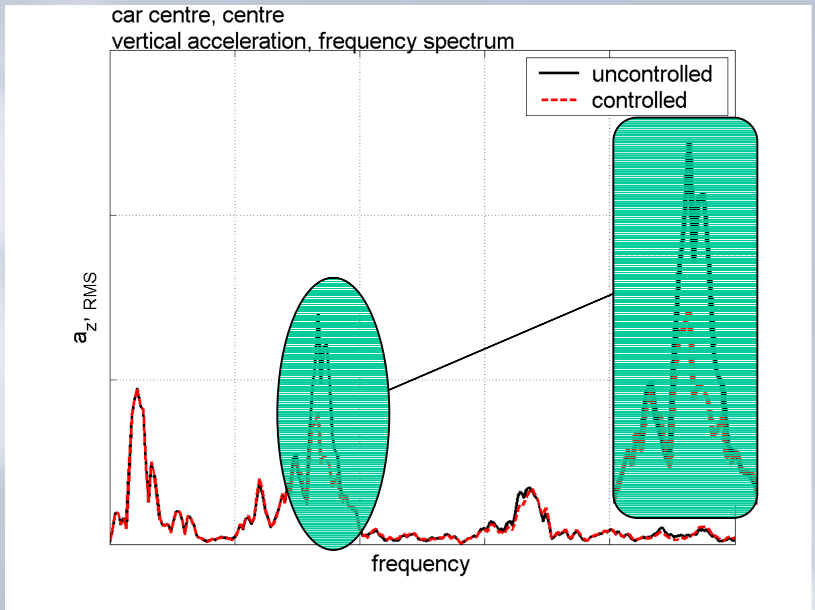
Vertical acceleration above bogie 1
near left sidewall, frequency spectrum

Simulation Results

Ride comfort on a straight track with irregularities DB High (considered period t=36s, s=800m, v=22m/s)



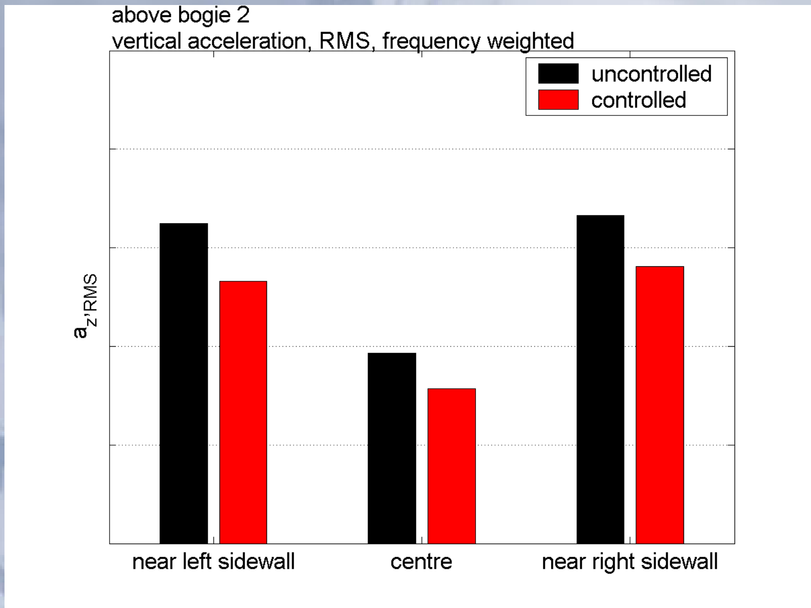
Vertical acceleration car centre ISO 2631 weighted RMS



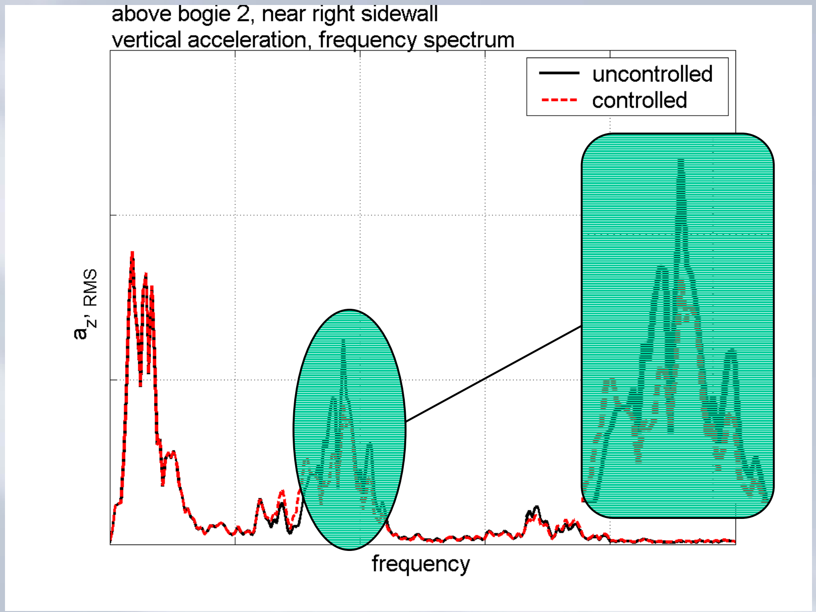
Vertical acceleration car centre centre, frequency spectrum

Simulation Results

Ride comfort on a straight track with irregularities DB High (considered period t=36s, s=800m, v=22m/s)

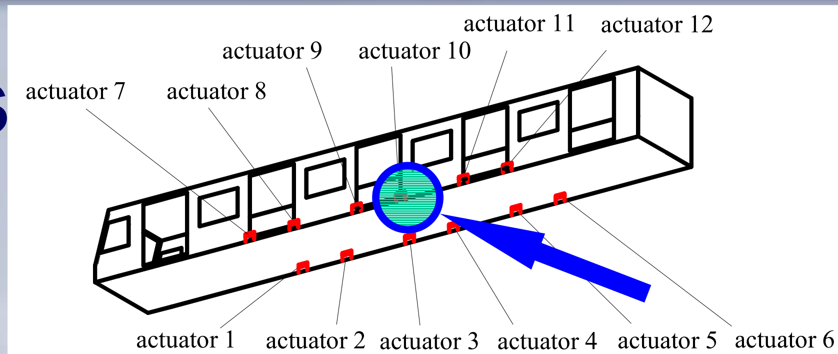


Vertical acceleration above bogie 2
ISO 2631 weighted RMS



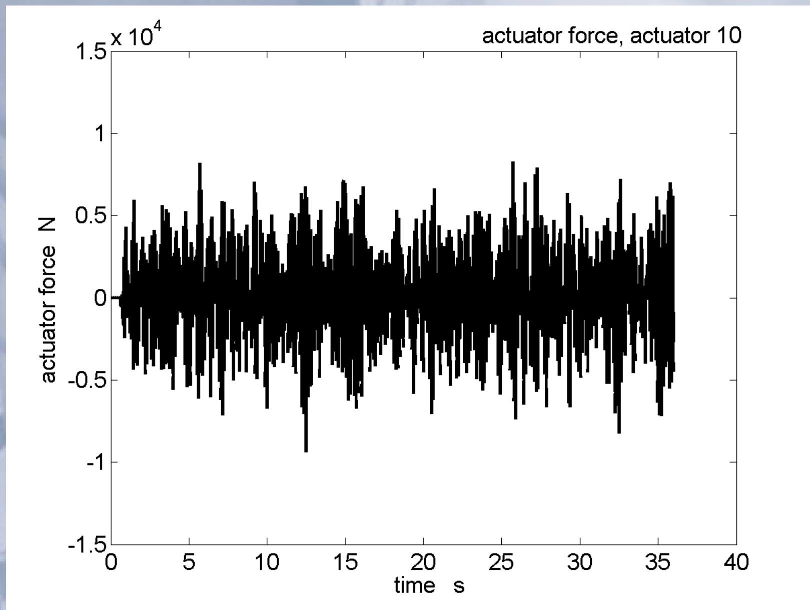
Vertical acceleration above bogie 2
near right sidewall, frequency spectrum

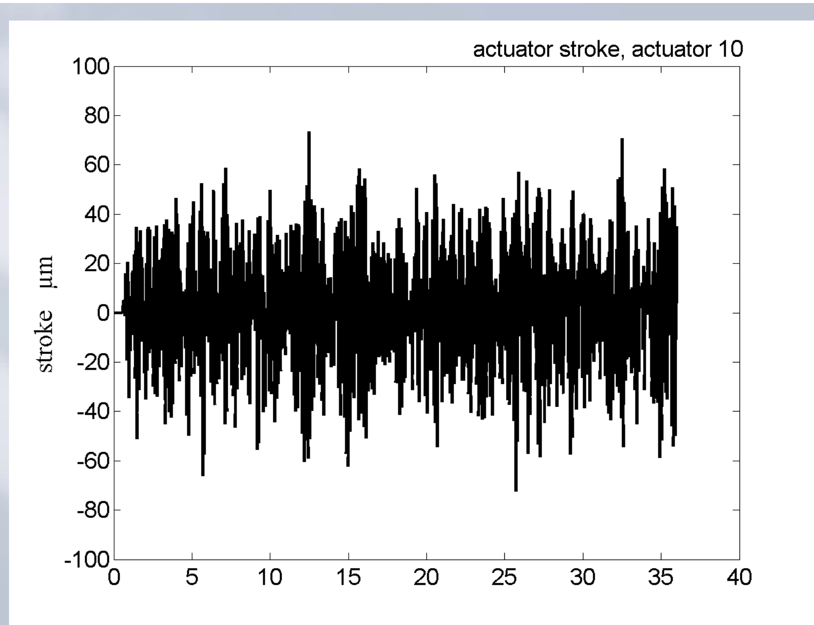
Simulation Results



Maximum actuator force and stroke

(actuator 10)





Actuator force, actuator 10

Conclusion and further activities

- **Simulation of complex controlled flexible multibody systems possible**
- **Investigation of more sophisticated control algorithms**
- **Investigation of controller robustness**
- **Optimization of sensor and actuator placement**