

A faded, light blue background image of a classical statue, likely the 'Athena' statue by Giovanni Stanetti, which is the emblem of TU Wien. The statue is a female figure with an owl on her head, holding a book and a torch.

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 $\mathbf{u}(\mathbf{R}, t) = \mathbf{\Phi}(\mathbf{R})\mathbf{q}(t)$

$\mathbf{\Phi}(\mathbf{R})$ eigenmodes, $\mathbf{q}(t)$ modal coordinates

- Modal mass matrix $\mathbf{M}_{ee} = \mathbf{\Phi}^T \mathbf{M} \mathbf{\Phi}$

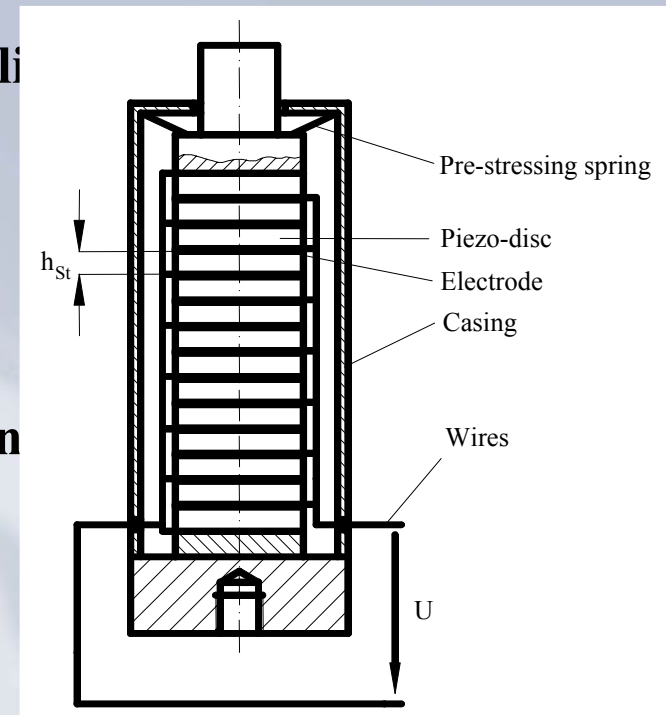
- Modal stiffness matrix $\mathbf{K}_{ee} = \mathbf{\Phi}^T \mathbf{K} \mathbf{\Phi}$

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

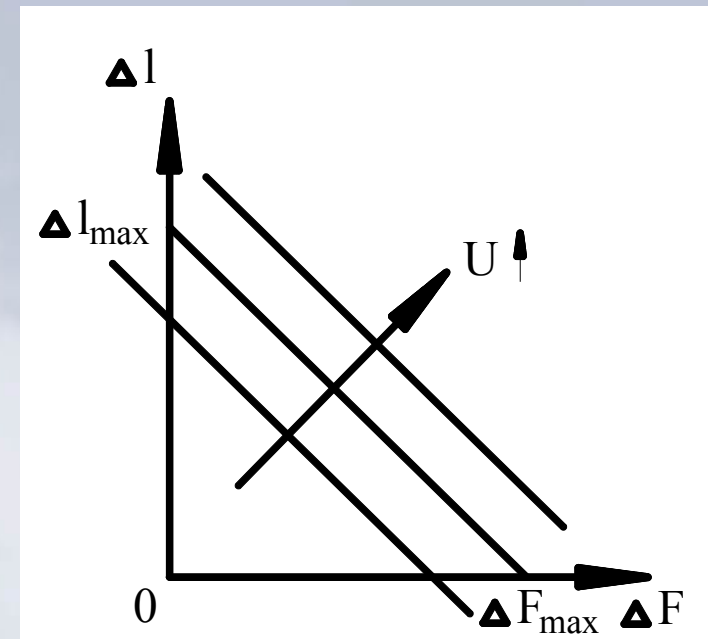
- **Actuator: applied voltage – strain or applied voltage - Force**
- **Sensor: Strain – electr. charge or strain - voltage**
- **Maximum stroke up to about 100 μm using stack actuators**
- **Maximum forces up to 10^5 N**



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

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

- Obtain linear state-space model:

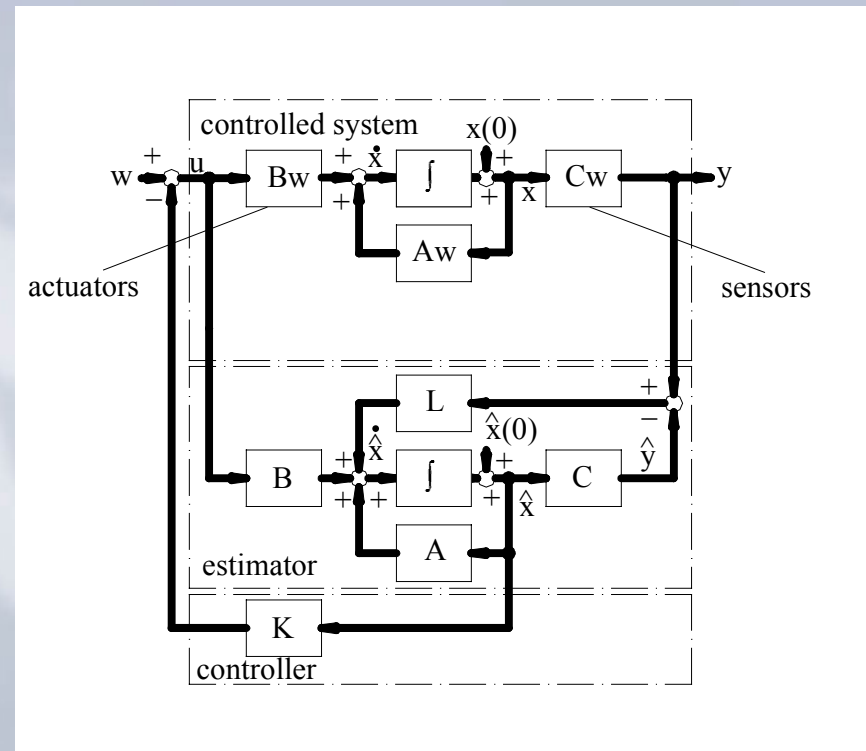
$$\mathbf{x} = (\mathbf{q} \quad \dot{\mathbf{q}})^T$$

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

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

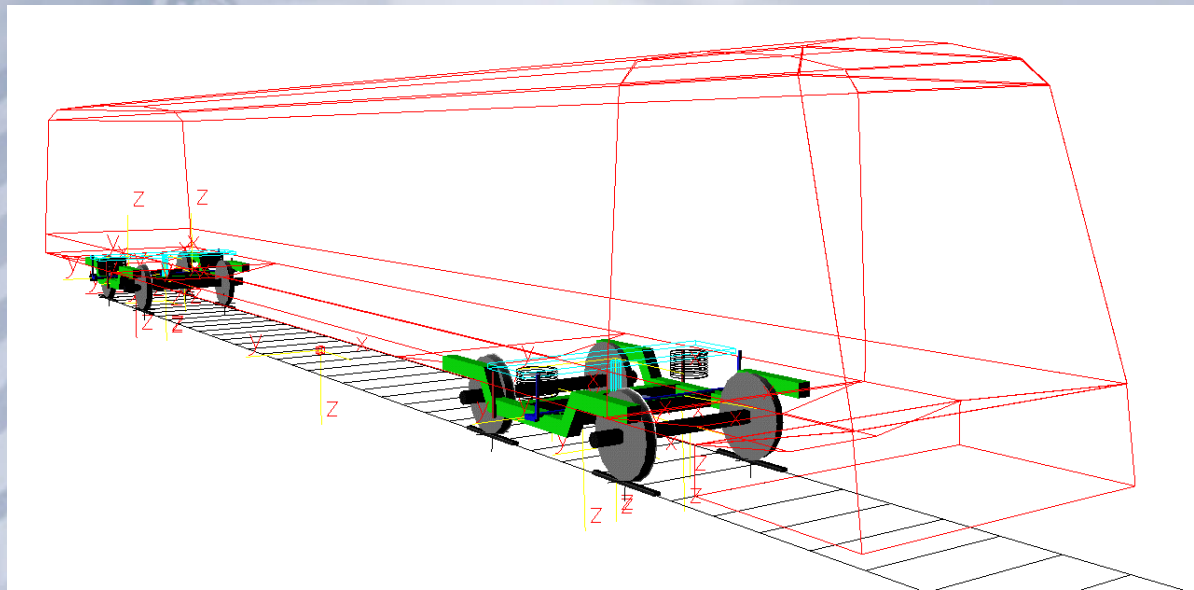
Controller Design

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



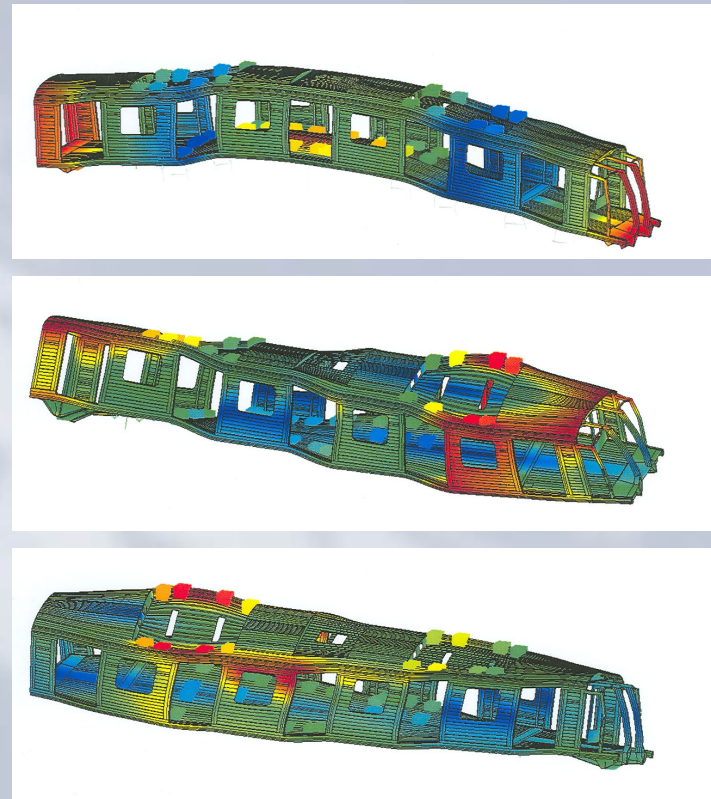
Co-Simulation using SIMPACK/Simulink

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



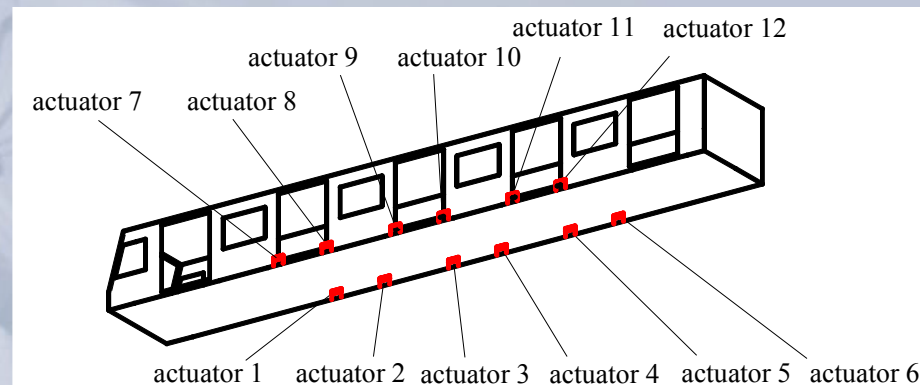
Co-Simulation using SIMPACK/Simulink

- Active vibration control –
damping of
 - 1st vertical bending mode
 - 1st torsion mode and
 - 1st diagonal distortion
- increased to 30 %



Co-Simulation using SIMPACK/Simulink

- **Placing of 12 actuators**



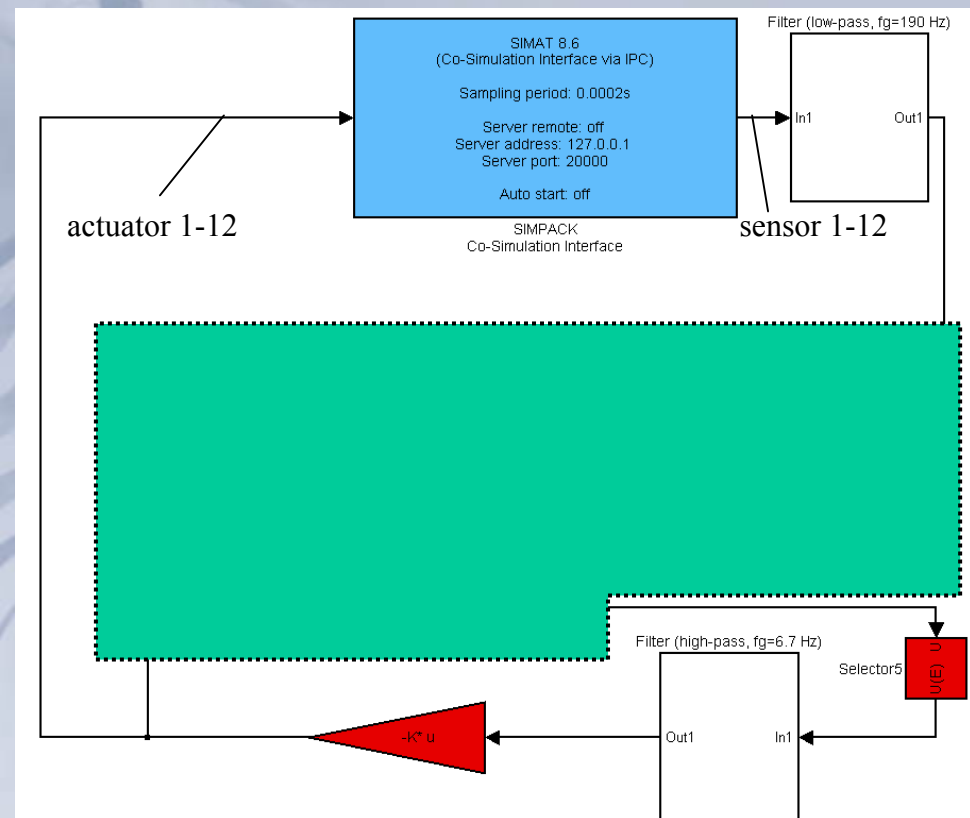
- **Calculation of 12 additional Frequency Response Modes**
- **Total of 29 shape functions for flexible car body**
- **Adding spring-damper elements at actuator positions to include actuator stiffness**
- **Placing 12 sensors at actuator positions**

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

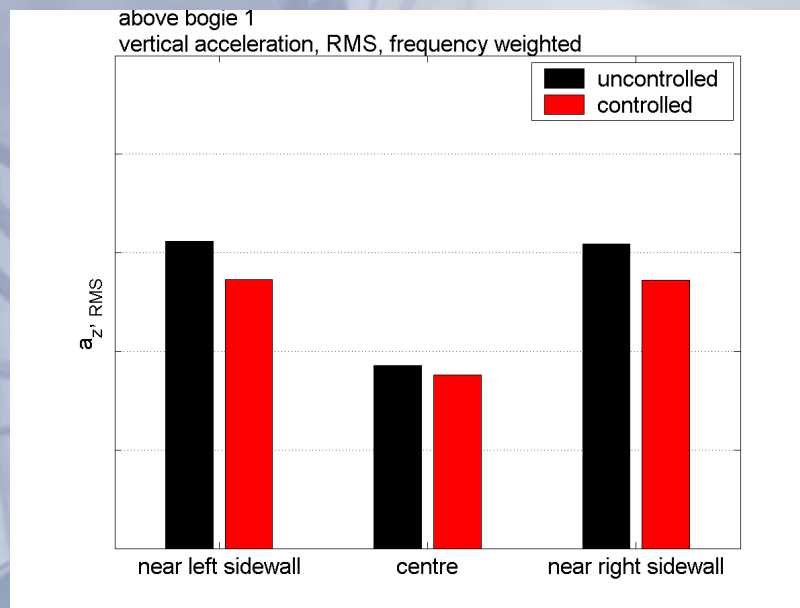
□ Observer based controller in Matlab/Simulink



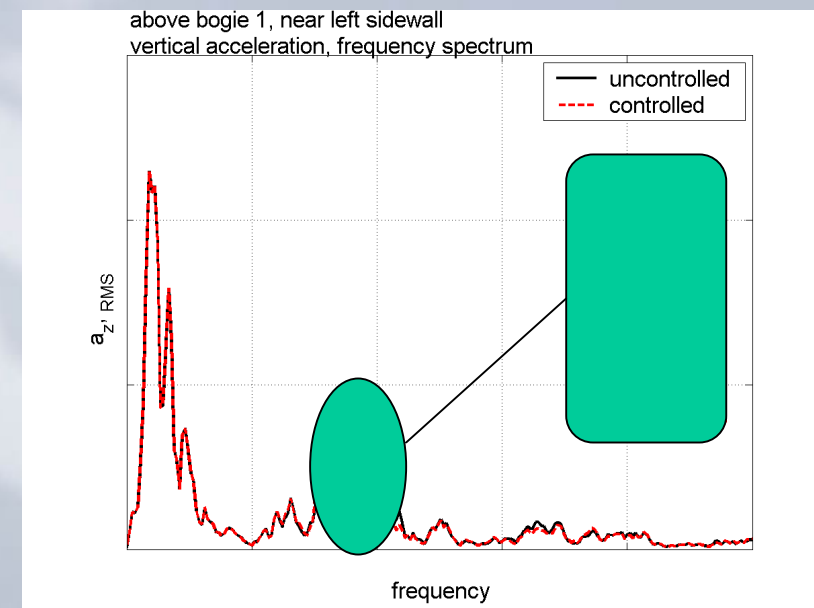
Simulation Results

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

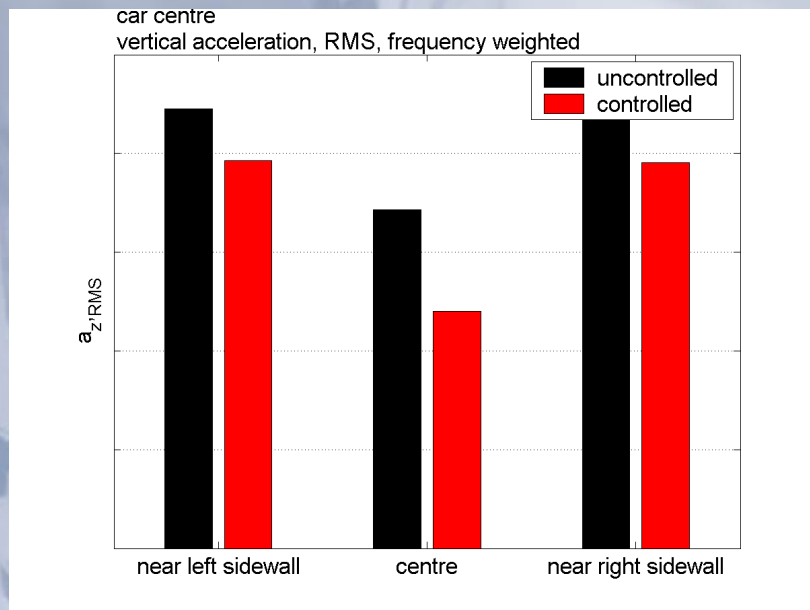


Vertical acceleration above bogie 1
near left sidewall, frequency spectrum

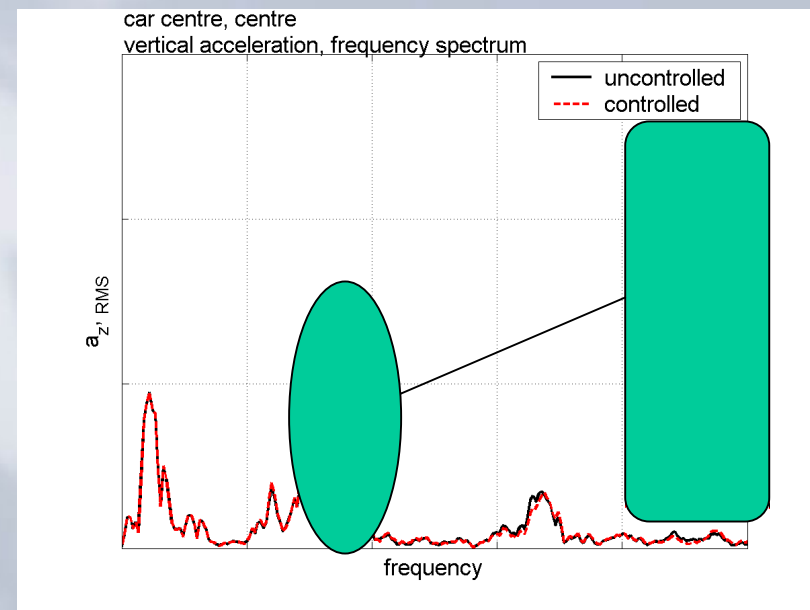
Simulation Results

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

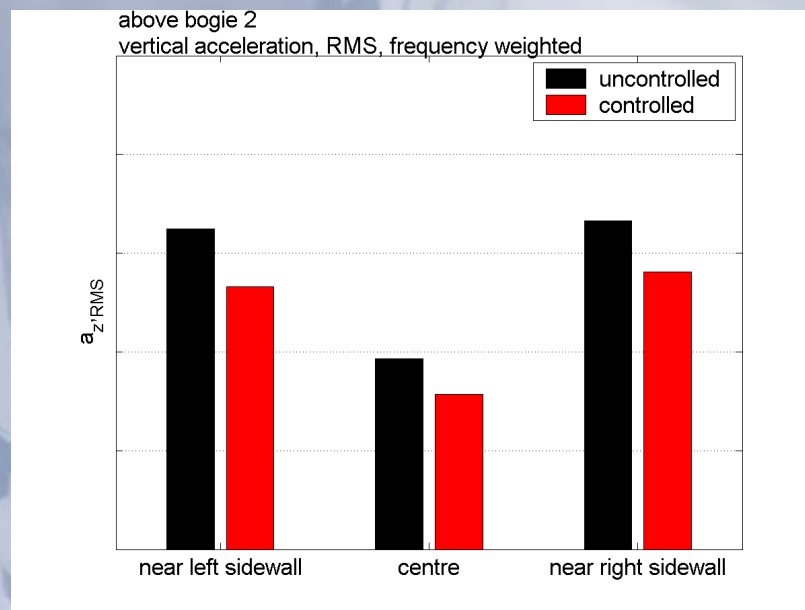


Vertical acceleration car centre
centre, frequency spectrum

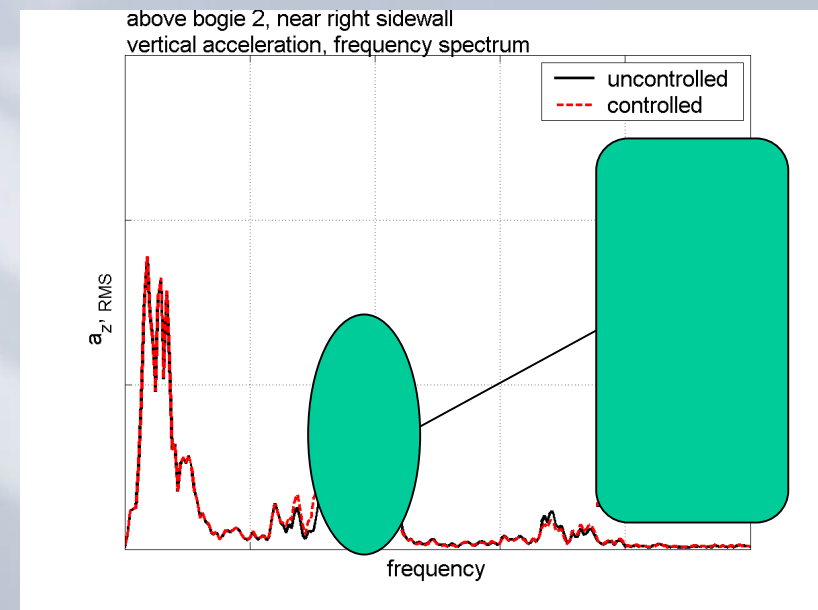
Simulation Results

Ride comfort on a straight track with irregularities DB High (considered period

$t=36s$, $s=800m$, $v=22m/s$)



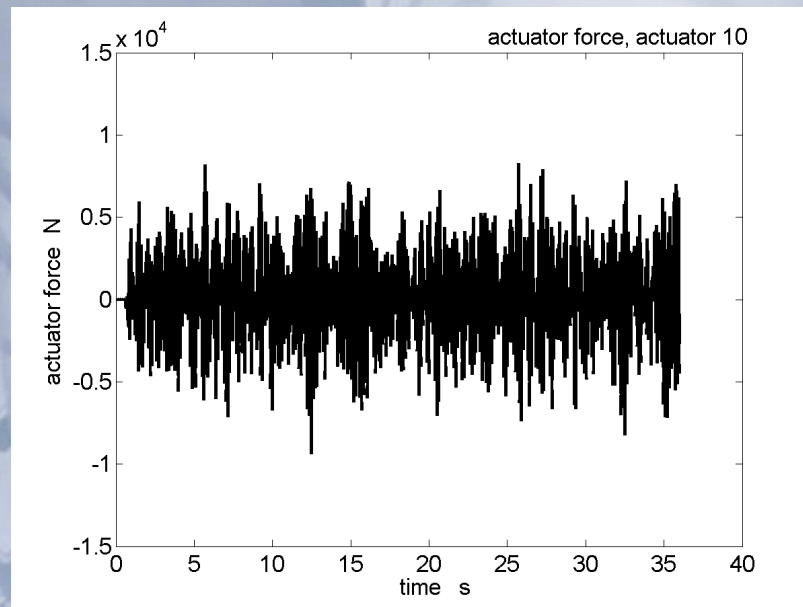
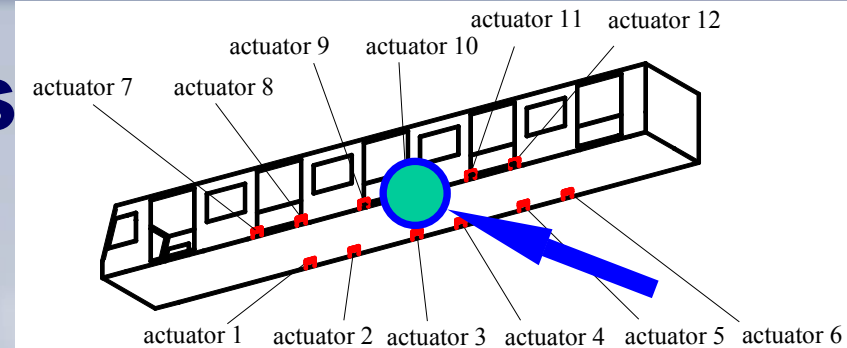
Vertical acceleration above bogie 2
ISO 2631 weighted RMS



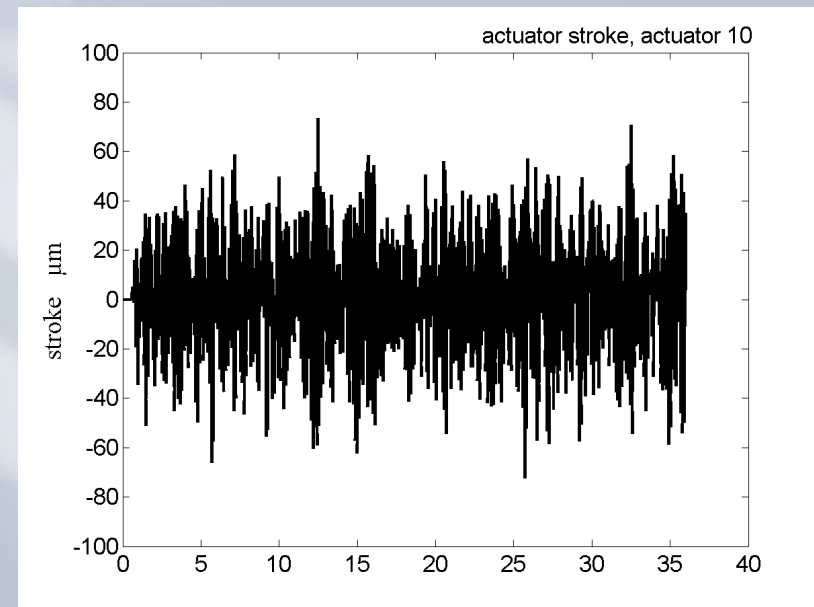
Vertical acceleration above bogie 2
near right sidewall, frequency spectrum

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**