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 \( u(R, t) = \Phi(R)q(t) \)
  - \( \Phi(R) \) eigenmodes, \( q(t) \) modal coordinates
- Modal mass matrix \( M_{ee} = \Phi^T M \Phi \)
- Modal stiffness matrix \( K_{ee} = \Phi^T K \Phi \)
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 $10^5 \, N$
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
  \[ M_{ee} \ddot{q} + D_{ee} \dot{q} + K_{ee} q = -K_{e\varphi} u_\varphi \]

- Sensor equation
  \[ Q_\varphi = K_{e\varphi}^T q + K_{\varphi\varphi} u_\varphi \]

- Obtain linear state-space model:
  \[ x = (q \quad \dot{q})^T \]
  \[ \dot{x} = Ax + Bu \quad y = Cx + Du \]

- 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, 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

- Frequency spectrum
  - Near right sidewall

![Graph showing vertical acceleration above bogie 2](image)
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