Aktive Schwingungsdämpfung an einer elastischen Wagenkasten-Struktur

Martin Kozek*, Christian Benatzky*, Alexander Schirrer* und Anton Stribersky +

* Institute of Mechanics and Mechatronics
+ Siemens Transportation Systems, Vienna, Austria

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Contents

• Motivation
• Fundamental concept
• Analytic modelling
• Experimental modelling - identification
• Robust controller design
• Actuator nonlinearities
• Co-simulation and experiment
• Conclusion
Motivation

Metro vehicles:
• Lightweight structures
• Simple, modular construction
• Many and large doors & windows

Poor ride comfort!

Active damping of vibrations:
• Secondary suspension (safety!),
  (Stribersky et.al. 1998, Foo & Goodall 2000)
• Actuators on flexible structure
  (Kamada et.al. 2005, Schandl et.al. 2007)
Elastic Deformations of Car Body

1st vertical bending mode

1st torsional mode

1st diagonal distortion mode
Innovative Solution

- Low power consumption
- Robust in case of system failure
- Small effect on suspension / rail/wheel forces
- Rigid body modes not controllable

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Active Damping Concept I

Piezo-stack actuator mounted in console:

Blocking force $F_B = 50\text{kN} @ 1\text{kV}$, travel $\Delta w = 0.2\text{mm}$, length $l = 294\text{mm}$, diameter $d = 45\text{mm}$, power $P_{\text{typ}} = 150\text{W}$
Active Damping Concept II

Actuator, sensor, and performance positions:

Symbols:
- ... Actuator
- ... Sensor
- ... Performance position
- ... Excitation force

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Analytic Modeling I

\[ M \ddot{w} + L \dot{w} + K w = f(t) \]

system of ODEs of order \( n \)

\[ w(t) = \Phi q(t) = \sum_{j=1}^{n} \phi_j q_j(t) \]

generalized coordinates \( w \) expressed by eigenvectors \( \Phi \) and modal coordinates \( q \)

\[ \ddot{q} + 2\zeta \Omega \dot{q} + \Omega^2 q = \mu^{-1} \Phi^T f(t) \]

system of modal ODEs

\[ x = [q, \dot{q}]^T \]

definition of state vector

\[ \dot{x} = Ax + B_1 d + B_2 u \quad y = C_2 x \]

state-space equations, order \( 2n \)

(Preumont 1997)

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Analytic Modeling II

Input matrices are composed of components of $\phi$ in direction of $w_i$ and $w_j$, respectively

\[ B_1 = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \phi_1(w_l) \\ \vdots \\ \phi_n(w_l) \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \phi_1(w_j) - \phi_1(w_i) \\ \vdots \\ \phi_n(w_j) - \phi_n(w_i) \end{bmatrix} \]

Only for collocation!
(Preumont 1997)
Non-collocation: similar to $B_2$

\[ C_2 = \frac{1}{l_s} B_2^T \]

Transfer functions from actuator to sensor and disturbance to sensor.

\[ G_{su} = C_2(sI - A)^{-1}B_2 \]
\[ G_{sd} = C_2(sI - A)^{-1}B_1 \]
Experimental Modeling - Identification

\[
\begin{bmatrix}
\dot{x} \\
z \\
y
\end{bmatrix} =
\begin{bmatrix}
A & B_1 & B_2 \\
C_1 & D_{11} & D_{12} \\
C_2 & D_{21} & D_{22}
\end{bmatrix}
\begin{bmatrix}
x \\
d \\
u
\end{bmatrix}
\]

direct identification of state-space system!

performance measurements
sensor measurements

measured data \rightarrow\text{variables } d, u, z, y \rightarrow \text{n4sid} \rightarrow \text{reference model order 200}

\text{removal of local modes} \rightarrow \text{balanced reduction} \rightarrow \text{reduced model for controller design}

(Benatzky et.al. 2007a)
Identification Results

- **empirical transfer function estimate**
- **full order state space model**
- **reduced order state space model**
  - for controller design

---

**Graphs:**

1. **Left Graph:**
   - Frequency in Hz
   - **$G_{z2d}$** in dB
   - **$G_{z2d, red}$** in dB
   - **$T_{z2d}$**
   - **Transfer function: action from $d$ to $z_2$**

2. **Right Graph:**
   - Frequency in Hz
   - **$G_{z2u1}$** in dB
   - **$G_{z2u1, red}$** in dB
   - **$T_{z2u1}$**
   - **Transfer function: action from $u_1$ to $z_2$**

---

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Robust $H_\infty$-Control

NOMINAL SYSTEM
(contains all weights)

UNCERTAINTY
(additive, multiplicative, parametric)

INPUTS
Uncertainties
Disturbances
Control inputs

OUTPUTS
Uncertainties
Performance outputs
Measurement outputs

CONTROLLER
Standard P-K- $\Delta$-Structure
Controller Design

Power spectrum densities of INPUT DISTURBANCES

PERFORMANCE (Accelerations, control inputs, etc.)

UNCERTAINTIES (Actuators→multiplicative, neglected dynamics→additive)

Design model of a flexible structure (e.g. modally reduced model)

Guaranteed robust performance by DK-iteration!

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Controller Comparison

active damping of acceleration \( (a_{\text{RMS,ISO}}) \) in %

<table>
<thead>
<tr>
<th>controller</th>
<th>F1</th>
<th>Fr</th>
<th>M1</th>
<th>Mr</th>
<th>Rl</th>
<th>Rr</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{DK1,e} )</td>
<td>33.0</td>
<td>34.7</td>
<td>6.4</td>
<td>2.7</td>
<td>41.4</td>
<td>33.1</td>
</tr>
<tr>
<td>( K_{DK2,e} )</td>
<td>38.7</td>
<td>40.9</td>
<td>6.7</td>
<td>5.1</td>
<td>47.2</td>
<td>37.3</td>
</tr>
<tr>
<td>( K_{DK3,e} )</td>
<td>40.2</td>
<td>44.9</td>
<td>4.9</td>
<td>1.8</td>
<td>47.4</td>
<td>34.7</td>
</tr>
<tr>
<td>( K_{PP,e} )</td>
<td>16.1</td>
<td>20.4</td>
<td>-6.2</td>
<td>-3.3</td>
<td>18.0</td>
<td>16.3</td>
</tr>
</tbody>
</table>

control cost in % of \( K_{PP,e} \)

<table>
<thead>
<tr>
<th>controller</th>
<th>( u_{1,\text{RMS}} )</th>
<th>( u_{2,\text{RMS}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{DK1,e} )</td>
<td>17.2</td>
<td>9.8</td>
</tr>
<tr>
<td>( K_{DK2,e} )</td>
<td>23.9</td>
<td>13.7</td>
</tr>
<tr>
<td>( K_{DK3,e} )</td>
<td>60.0</td>
<td>31.7</td>
</tr>
<tr>
<td>( K_{PP,e} )</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

(Benatzky et.al. 2007b)

\( H\infty \)-Control vs. Pole-Placement

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Full-size actuator

Experimental validation of feasibility:

- Real-time computer (controller)
- Signal conditioning
- Amplifier
- Console
- Piezo-stack

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Nonlinear Actuator: Model and Control

- Control system

  ![Control system diagram](image)

- Hysteresis loops

  ![Hysteresis loops diagram](image)

- Force deviation, measured

  ![Force deviation diagram](image)

(Schirrer et al. 2008b)

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Co-Simulation

Comprehensive and complex co-simulation with MATLAB & SIMPACK:

Rail irregularities, wheel-rail contact, bogies, suspensions, FE-car body

Nonlinear actuator

(Schirrer et.al. 2008b)

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Results of Co-Simulation

PSD – plots for actuator cfg. „door/roof“ (v=80km/h, DB-High)
Scaled car body (1:10) made from aluminum:

- Amplifier
- 2 Piezo-stack actuators
- Shaker
- (2 Piezo-patch sensors)
- Soft coil springs

The figure shows a scaled car body with a shaker on one end and two piezo-stack actuators on the other. The diagram also includes a table with eigenmode information:

<table>
<thead>
<tr>
<th>#</th>
<th>eigenmode</th>
<th>$\omega_i$ in Hz</th>
<th>$\zeta_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>vertical bending</td>
<td>65.66</td>
<td>0.0037</td>
</tr>
<tr>
<td>2</td>
<td>torsion</td>
<td>73.91</td>
<td>0.0043</td>
</tr>
<tr>
<td>3</td>
<td>diagonal distortion</td>
<td>101.72</td>
<td>0.0030</td>
</tr>
</tbody>
</table>

(Kozek et.al. 2008)
Results from experimental model

accelerations at four performance positions:

left

front

middle

right

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Experimental results II

Verification of unchanged mode shapes using a Laser vibrometer:

torsion @ 71.8Hz:
amplitude reduction
120nm → 40nm

(bending @ 91.3Hz:
amplitude reduction
50nm → 30nm

(open-loop)

(closed-loop)

(Popprath et.al. 2007)

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Further Results

• Nonlinear identification of Piezo-hysteresis (experimental), Schirrer & Kozek, ENOC-08.

• Laser speckle interferometry for analysis of console strain, Schirrer et.al., ICSV15.

• Fault detection and isolation by hardware redundancy, Benatzky & Kozek, ICSV14.
Conclusion

• Innovative concept for active damping of a flexible car body using Piezo-actuators
• Piezo-stack actuators mounted in consoles
• Non-linear actuator model and compensation
• Robust $H_\infty$-control system
• Feasibility is validated by
  – Complex co-simulation
  – Scaled metro model with closed-loop experiment
  – Full-size actuator experiments
• Very large structure for Piezo application

GMA/GAMM-Workshops, Sept. 21-26.09.2008, Salzburg
Kozek, M., Bilkic, C., Benatzky, C., 2006. A pc-based flexible solution for virtual instrumenta