Theoretical and Experimental Research of the Vertical Dynamics of an Electric Wheelchair

An approach to improve the Ride Comfort using Semi-Active Dampers

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Concept of the R&D - Project LoCoMS\textsuperscript{1}

Development of a Low-Cost Development Environment for Mechatronic Systems

Example

Application

Noise

Active Noise Reduction

Partner

Software & Systems

Transfer of Knowledge

Software Development

Vibration

Reduction of Human Vibration

\textsuperscript{1} Low-Cost Mechatronic Systems

- Example
- Application
- Noise
- Active Noise Reduction
- Partner
- Software & Systems
- Transfer of Knowledge
- Software Development
- Vibration
- Reduction of Human Vibration
- Low-Cost Mechatronic Systems
Attributes of the Wheelchair

- Electric Wheelchair for use in indoor and outdoor areas (up to 10 km/h)
- Fully suspended chassis with special swing arms
- Spring-Damper elements well-established in the bicycle industry
- Short wheelbase for increased agility
- Hard suspension of wheelchair in spite of using spring-damper elements

Aim

- Understanding the wheelchair’s dynamic
- Improvement of ride comfort

Mechatronic Approach:

- Use of semi-active controlled electro-rheological damper
Aim: Improvement of Ride Comfort

Experiment
- Road Test
- Test Rig

Verification

Simulation
- MBS-Model Wheelchair
- Damper-Model
- Damper-Control

Approach

Virtual Realization

Technical Realization

Storm^4 X-plore
Ride Comfort and System Behaviour

Transfer Behaviour

Ride Comfort

Road Excitation

Wheelchair

Human Cognition

ISO 2631-1

Restricted Element
Minor Aspects of the Project

- Design of a Dummy according to DIN 45676
  Mechanical impedances at the driving point and transfer functions of the human body
- Measurement of the road's profile
- Design of a test rig using an eccentric for the excitation of one wheel
Vertical Dynamic Analysis on Cobblestone

- Resonances Wheelchair
- Vertical Resonance of the Human
- Dämpfer im Anschlag
- Dämpfer im Arbeitspunkt
- Dämpfer im Arbeitspunkt ohne Öl

Frequenz [Hz]

Beschleunigung [m/s²]
Vertical Dynamic Analysis on the Test Rig

![Graph showing vertical resonances and transfer function](graph.png)

- Resonances Wheelchair
- Vertical Resonance of the Dummy / Human
Influence of the Passive Suspension Damping on the Ride Comfort

- Increasing the suspension damping leads to unexpected bad ride comfort
Multi - Body Simulation

Model Data:
- 11 Bodies
- 21 Degrees of Freedom
- 10 Force Elements

- Fast Modeling from CAD-Data (Geometry and Inertia)
- Desired improvement: Using Geometry to define Joints and Force Elements
Modeling of the Tires and Dampers

- For the real Dampers, no models with parameters exist
- Realization of suspension dampers proportional to velocity through experimental analysis
- Tires consisting of rigid bodies
- Non-linear stiffness and damping proportional to velocity (compression only) exist between the tires and the ground

**Aim:** Simulation of bench tests and road excitation (horizontal dynamic excluded)
Modeling of Road Excitation

Leistungsdichtespektrum der Fahrbahn im Frequenzbereich

Input-Funktion des Leistungsdichtespektrums

Leistungsdichtespektrum aus Inputfunktion

Synthetisches Fahrbahnsignal aus PSD

Input-Function

Type 2: PSD by Input-Function

Type 8: Stochastic Excitation from PSD
Verification of the MBS-Model without Viscous Damping

- Messung - N1 Prüfstand Dämpfer defekt in Arbeitspunkt
- Simulation - N1 Prüfstand Dämpfer defekt in Arbeitspunkt

vertical Resonance
Dummy
Resonance Wheelchair

Transferfunktion $z_{N1} / z_{NA}$

Frequency [Hz]
Verification of the MBS-Model with Viscous Damping

Transfer function $Z_{N1}/Z_{NA}$ vs. Frequency [Hz]

- Blue line: Measurement - N1 Prüfstand Dämpfer intakt in Arbeitspunkt
- Red line: Simulation - N1 Prüfstand Dämpfer intakt in Arbeitspunkt

- Resonance Wheelchair
- Vertical Resonance Dummy
- Simulation
- Measurement
Eigenvalue Analysis of the MBS-Model

Modal Analysis enables the study of different resonance effects
- Roll (5.8 Hz) and Vertical Eigenfrequency (8.4 Hz) are in the sensitive frequency range of the human body (≈ 4Hz - 9 Hz)
- Pitch-Eigenfrequency is at 2.5 Hz
Influence of the Wheelbase on the Ride Comfort

\[ f_{\text{vertical}} = \frac{2(l^2k)}{J} \]
\[ f_{\text{pitch}} = \sqrt{\frac{2k}{m}} \]

Radstand / m

Ride Comfort

Quelle: Daimler AG
Mechatronic Approach with MBS
**Damper with Electro-Rheological Fluid**

ER-Damper by Fludicon

Formation of Chain Structures

Polarisierbare Polymere
Trägerflüssigkeit

Kettenstrukturen
Elektrische Feldlinien

Bingham-Model

\[ F_{\text{Bingham}} = b_B \cdot \varepsilon + f_B \]

**Damper Characteristic**

Voltage

- Voltage
- Damper Characteristic
- Quelle: Fludicon
- Bingham-Model
- Formation of Chain Structures
- Polarisierbare Polymere
- Trägerflüssigkeit
- Kettenstrukturen
- Elektrische Feldlinien
System Behaviour

Passive

Active (Skyhook)
Semi-Active Control with Electro-Rheological Damper

Skyhook-Algorithm

\[ b_{sky} = \begin{cases} \ b_{max} & \text{für } \dot{z} \cdot (\dot{z} - \dot{\omega}) > 0 \\ \ b_{min} & \text{für } \dot{z} \cdot (\dot{z} - \dot{\omega}) \leq 0 \end{cases} \]

\[ F_{sky} = b_{sky} \cdot \dot{z} \]
Co-Simulation of Semi-Active Damped Wheelchair
Simulation Results

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Simulation RMS $a_{zw}$ Seat</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Skyhook Damper Control</td>
<td>1,89 m/s²</td>
<td></td>
</tr>
<tr>
<td>With Skyhook Damper Control</td>
<td>1,87 m/s²</td>
<td>1,07 %</td>
</tr>
</tbody>
</table>

**No improvement** of ride comfort by using semi-active damper

Why do no improvements occur?
Case Study (2 DOF System) with Skyhook-Control

- Improvements of 26% compared to optimal passive damped system
- No improvement with high inherent damping $D > 0.3$
Realization of Semi-Active Damper Control

- **cDAQ**: (Data-Aquisition)
- **cRIO**: (Signal-Processing & Damper Control)
- **Distance Sensor**: (Damper-Velocity)
- **Accelerometer**: (Chassis-Velocity)
- **Electro-Rheological Damper**
Semi-Active Control on a Prototype

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No improvement of ride comfort by using semi-active damper control

Confirmation of simulation results
Conclusion

- MBS is an important component of a mechatronic development environment
- MBS avoids the development of physical, expensive prototypes
- MBS reduces the time of development
- Semi-Active Skyhook-Control is not able to produce comfort improvements on systems with high inherent damping (D>0.3)
- The results of the MBS-simulation have been confirmed through use of a prototype

Thank you for your attention!