ROBUST SEMI-ACTIVE RIDE CONTROL UNDER STOCHASTIC EXCITATION

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Robust Semi-Active Ride Control Under Stochastic Excitation

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Outline

• Introduction/Overview
• Vehicle Modeling
• Road Profile and Stochastic Excitation
• Performance Metrics
• Control Methodology
• Simulation Results
  • Robust for parameter range
  • Robust for unknown input
  • Comparison
• Conclusions
Ride comfort for military vehicles are important for several reasons:
1) Fatigue caused by vehicle vibrations
2) Motion sickness reduction by smoothed vehicle motions
3) Ability to modify handing conditions based upon terrain

Suspension Type:
1) Fully Active Suspension
2) Passive Suspension
3) Semi-Active Suspension

Control Method:
1) LQR/H-Infinity/Linear Methods
2) Nonlinear/Adaptive
3) Discontinuous (Parameterized or otherwise)
Seven Degree of Freedom Vehicle Model

Suspension Forces

\[ F_{fl} = k_{fl}(z - a \theta + l\phi - z_{fl}) + c_{fl}(\dot{z} - a\dot{\theta} + l\dot{\phi} - \dot{z}_{fl}) \]  
\[ F_{fr} = k_{fr}(z - a \theta - r\phi - z_{fr}) + c_{fr}(\dot{z} - a\dot{\theta} - r\dot{\phi} - \dot{z}_{fr}) \]  
\[ F_{rl} = k_{rl}(z + b \theta + l\phi - z_{rl}) + c_{rl}(\dot{z} + b\dot{\theta} + l\dot{\phi} - \dot{z}_{rl}) \]  
\[ F_{rr} = k_{rr}(z + b \theta - r\phi - z_{rr}) + c_{rr}(\dot{z} + b\dot{\theta} - r\dot{\phi} - \dot{z}_{rr}) \]

Wheel Dynamics

\[ \ddot{z}_{fl} = \frac{-k_{u,fl}*(z_{fl} - z_{g,fl})H(z_{g,fl} - z_{rl}) + F_{fl}}{m_{rl}} - g \]  
\[ \ddot{z}_{fr} = \frac{-k_{u,fr}*(z_{fr} - z_{g,fr})H(z_{g,fr} - z_{fr}) + F_{fr}}{m_{fr}} - g \]  
\[ \ddot{z}_{rl} = \frac{-k_{u,rl}*(z_{rl} - z_{g,rl})H(z_{g,rl} - z_{rl}) + F_{rl}}{m_{rl}} - g \]  
\[ \ddot{z}_{rr} = \frac{-k_{u,rr}*(z_{rr} - z_{g,rr})H(z_{g,rr} - z_{rr}) + F_{rr}}{m_{rr}} - g \]

Vehicle Body Dynamics

\[ \ddot{z} = \frac{-(F_{fl} + F_{fr} + F_{rl} + F_{rr})}{mass} - g \]  
\[ \dot{\theta} = \frac{a(F_{fl} + F_{fr}) - b(F_{rl} + F_{rr})}{J_{pitch}} \]  
\[ \dot{\phi} = \frac{-l(F_{fl} + F_{rl}) + r(F_{fr} + F_{rr})}{J_{roll}} \]
Third Order Auto Regressive Time-Series Model

\[ u_i = \phi_1 u_{i-1} + \phi_2 u_{i-2} + \phi_3 u_{i-3} + \varepsilon_i \]  \hspace{1cm} (12)

Feedback Coefficients

\[ \phi_1 = 1.2456, \]
\[ \phi_2 = -0.2976, \]
\[ \phi_3 = -0.1954, \]
\[ \varepsilon_i = \text{Gaussian White Noise, Unity Variance} \]

A series of statistical tests were conducted to examine the validity of the time-series model representation of the road profile
Third Order Auto Regressive Model

\[ u_i = \phi_1 u_{i-1} + \phi_2 u_{i-2} + \phi_3 u_{i-3} + \varepsilon_i \]  \hspace{1cm} (12)

Front-Left-Wheel: \[ z_{w_{fl}}(t) = z_r(t) = u_i \]
Front-Right-Wheel: \[ z_{w_{fr}}(t) = z_r(t + \delta) = u_{i+\delta} \]
Rear-Left-Wheel: \[ z_{w_{rl}}(t) = z_r\left(t + \frac{L}{v_s}\right) = u_{i+\frac{L}{v_s}} \]
Rear-Right-Wheel: \[ z_{w_{rr}}(t) = z_r(t + \frac{L}{v_s} + \delta) = u_{i+\frac{L}{v_s}+\delta} \]

Wheelbase: \( L \) \hspace{1cm} Vehicle Speed: \( v_s \) \hspace{1cm} Delay: \( \delta \)
Performance Metrics

- **Absorbed Power (At the seat locations)**
  - Next Slide

- **RMS Acceleration (At the seat locations)**
  - $\sqrt{\ddot{z}/N}$

- **Road Holding (At each wheel)**
  - $z_{\text{wheel}} - z_{\text{road}}$

- **Rattle Space (For each suspension strut)**
  - $z_{\text{body}} - z_{\text{wheel}}$
• **Absorbed Power**
  • Measure of ride comfort
  • Amount of energy absorbed from ride vibration

\[
\overline{AP} = \lim_{T \to \infty} \frac{1}{T} \int_0^T F(t)V(t) dt
\]

• Actual absorbed power with physical characteristics
• Typical coefficients of a 50th percentile man are used
• For the 7-DOF model, the absorbed power is computed at all the four seats (two in front and two in rear), and averaged to represent a single ride comfort metric used for the study.
Control Methodology – Accelerometer Driven Damper (ADD)

Infinite Control Authority ADD

\[ C_{desired} = C_{min} + H(\ddot{z}_{def})(C_{max} - C_{min}) \]  \hspace{1cm} (13)

Moving Average Filter

\[ Z_k = \sum_{i=0}^{N} \frac{1}{N+1} z_{k-i} \]  \hspace{1cm} (14)
Simulation Results – Parameter Effects

Response Surface for Varying Sliding Window Length and Damping

- Mean Absorbed Power
- Damping (Ns/M)
- Sliding Window Length (points)
Simulation Results – Parameter Effects

Absorbed Power Response for Varying Moving Average Length and Mass

Mean Absorbed Power

Mass (kg)

Filter Length (points)
Simulation Results – Stochastic Road Effects

Response Surface for Varying Sliding Window Length and Road Roughness, 15 MPH

- Mean Absorbed Power
- Sliding Window Length (points)
- Road Variance (inch)
Simulation Results – Stochastic Road Effects

Response Surface for Varying Sliding Window Length and Road Roughness, 30 MPH

Mean Absorbed Power

Sliding Window Length (points)

Road Variance (inch)
### Quarter Car Results

<table>
<thead>
<tr>
<th>Control Type</th>
<th>Average Absorbed Power (W)</th>
<th>Sprung Mass Acceleration RMS (g's)</th>
<th>Road Holding Max (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>26.65</td>
<td>0.61</td>
<td>4.45</td>
</tr>
<tr>
<td>SH 2-state</td>
<td>6.19</td>
<td>0.39</td>
<td>4.87</td>
</tr>
<tr>
<td>SH-ADD</td>
<td>3.43</td>
<td>0.25</td>
<td>4.87</td>
</tr>
<tr>
<td>SH Linear</td>
<td>3.05</td>
<td>0.23</td>
<td>5.54</td>
</tr>
<tr>
<td>ADD</td>
<td>1.28</td>
<td>0.19</td>
<td>5.11</td>
</tr>
<tr>
<td>Smoothed ADD (Proposed)</td>
<td>1.09</td>
<td>0.17</td>
<td>5.18</td>
</tr>
</tbody>
</table>
Conclusions

• Smoothing function significantly improves over the original ADD control for the higher fidelity models than just quarter car models.

• Invariant with respect to vehicle mass/inertia (Does not require any vehicle parameters)

• Invariant with respect to road profile

• Computationally efficient algorithm. Challenge comes from sensor implementation