Simulation of Vehicle Dynamics Control by active Steering Systems

Volker Dorsch, Faculty of Mechanical Engineering
Overview

- Development scenario
- Validated mechanical multibody simulation (MBS) vehicle model
- Implementation of active steering at rear and front wheels
- Control strategy
- Co-Simulation of Simpack and Matlab/Simulink®
- Simulation Results
- Conclusions
Development Scenario

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MBS Model: Coordinates

Input:
- $\delta_V$ – front steering angle
- $\delta_H$ – rear steering angle
- (v - velocity)

Output:
- $\psi$ – yaw rate
- $\beta$ – side slip angle
- $a_y$ – lateral acceleration
Validation

Suspensions: simulation of Kinematics and Compliance (K&C) measurements

Complete vehicle model: step steering input maneuver

<table>
<thead>
<tr>
<th>driver</th>
<th>objective, no driver influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>velocity</td>
<td>100 km/h</td>
</tr>
<tr>
<td>front wheel steering angle</td>
<td>sudden steering angle with more than 200 deg/s steady-state lateral acceleration is 0.4 g</td>
</tr>
<tr>
<td>road surface</td>
<td>dry, $\mu = 0.9$</td>
</tr>
</tbody>
</table>
Simpack model validation: Step Steering Input

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Simpack model validation: Step Steering Input

good correlation – realistic response of vehicle model
Active front and rear wheel steering

Simple implementation by

- additional rotational degrees of freedom at the corresponding wheels
- control of these degrees of freedom by external input of the co-simulated Matlab/Simulink controller model

Study of effects on vehicle dynamics
Vehicle stabilization by adjusted steering angles

Active rear wheel steering: adjust tire slip angle $\alpha$ by rear wheel steering angle

Active front wheel steering: adjust tire slip angle $\alpha$ by superimposed steering angle
Control algorithm: bicycle model

Equations of motion with linearized tire behavior: \( F_S = C_\alpha \alpha \)

\[
\begin{align*}
\ddot{\psi} &= \frac{C_{a_H} l_H - C_{a_V} l_V}{J_z} \dot{\beta} - \frac{C_{a_H} l_H^2 + C_{a_V} l_V^2}{J_z \dot{v}} \dot{\psi} + \frac{C_{a_V} l_V}{J_z} \delta_v - \frac{C_{a_H} l_H}{J_z} \delta_H \\
\dot{\beta} &= -\frac{C_{a_V} + C_{a_H}}{m v} \dot{\beta} + \left[ \frac{C_{a_H} l_H - C_{a_V} l_V}{m v^2} - 1 \right] \dot{\psi} + \frac{C_{a_V}}{m v} \delta_v + \frac{C_{a_H}}{m v} \delta_H
\end{align*}
\]
In case of steady-state cornering (i.e. $\dot{\Psi} = 0$ and $\dot{\beta} = 0$) without rear wheel angle

$$\dot{\Psi} = \frac{v_x \delta_w}{(l_V + l_H)(1 + \frac{v_x^2}{v_{ch}^2})}$$

The characteristic velocity $v_{ch}$ can be computed (or be identified in tests)

$$v_{ch} = \frac{C_{\alpha V} C_{\alpha H} l^2}{m(C_{\alpha H} l_H - C_{\alpha V} l_V)}$$

Furthermore the maximum yaw rate is limited

$$|\dot{\Psi}| \leq \frac{a_{y,max}}{v_x}$$

The yaw rate $\dot{\Psi}$ is used as desired yaw rate in the control algorithm.
Setting $\dot{\beta}=0$ and $\beta=0$ in the differential equations of the bicycle model yields

$$\frac{\delta_H(s)}{\delta_V(s)} = K_{\delta_H} \frac{1+T_z s}{1+T_1 s}$$

with

$$K_{\delta_H} = \frac{C_{\alpha V} C_{\alpha H} l_H l - C_{\alpha V} l_V m v^2}{C_{\alpha V} C_{\alpha H} l_V l + C_{\alpha H} l_H m v^2},$$

$$T_z = \frac{J_{\dot{\beta}} v}{C_{\alpha H} l_H l - l_V m v^2},$$

$$T_1 = \frac{J_{\dot{\beta}} v}{C_{\alpha V} l_V l - l_H m v^2}.$$

The steady-state case with $K_{\delta_H}$ results in a characteristic diagram, that is used as a first prediction of the rear wheel steering angle.
Control algorithm: predict rear wheel steering angle

Open-loop rear wheel steering angle as predictor

low velocities and large front wheel steering angle:

high velocities and small front wheel steering angle:
Active rear wheel steering:
Control structure with co-simulation

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Active front wheel steering: Control structure with co-simulation
Steering angle orientation

Active rear wheel steering

\[ |\Psi_{des} - |\Psi| < 0 \quad \text{oversteer} \]
\[ |\Psi_{des} - |\Psi| \approx 0 \quad \text{neutral} \]
\[ |\Psi_{des} - |\Psi| > 0 \quad \text{understeer} \]

\[ \Psi > 0 \quad \text{left turn} \]
\[ \Psi < 0 \quad \text{right turn} \]

Tolerance function to avoid hard switch on – switch off effect
Co-Simulation: Input - Output

- Simpack and Matlab/Simulink\(^\circledR\) run parallel
- Data exchange at each millisecond
- Relatively slow motion of the whole vehicle: uncritical

**u-vector:** \(\delta_H, \Delta \delta_V\)

**y-vector:**
- velocity
- yaw rate
- \(\delta_H, \delta_V\)
# Maneuver steady-state cornering

<table>
<thead>
<tr>
<th>Driver</th>
<th>Simpack driver model, driver influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>increasing up to 75 km/h</td>
</tr>
<tr>
<td>Track</td>
<td>Circle with 80 m radius</td>
</tr>
<tr>
<td>Steering wheel angle input</td>
<td>closed loop, by driver</td>
</tr>
<tr>
<td>Road surface</td>
<td>dry, $\mu = 0.9$</td>
</tr>
</tbody>
</table>
Steady-state cornering: simulation results

Figure: Simulation results for different steering control strategies. The left graph shows the steering wheel angle in degrees as a function of lateral acceleration in m/s^2. The right graph illustrates the steering angles over time in seconds. Three scenarios are compared:

- Without control
- Active rear wheel steering
- Active front wheel steering

The graphs demonstrate the effectiveness of active steering systems in maintaining stability and control during steady-state cornering.
Steady-state cornering: simulation results

Change of cornering behavior by change of bicycle model parameters in the control algorithm

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Maneuver step steering input

<table>
<thead>
<tr>
<th>Category</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>objective, no driver influence</td>
</tr>
<tr>
<td>Velocity</td>
<td>80 km/h</td>
</tr>
<tr>
<td>Steering wheel angle input</td>
<td>sudden steering angle step with more than 200 deg/s, steady-state lateral acceleration is 0.4 g</td>
</tr>
<tr>
<td>Road surface</td>
<td>dry, $\mu = 0.9$</td>
</tr>
</tbody>
</table>
Step steering input: simulation results

![Graphs showing yaw rate and lateral acceleration comparison between different steering systems.](image)

- **Peak reduction**
Step steering input: simulation results

[Graph showing side slip angle and active wheel steering angle over time]

- Without control
- Active rear wheel steering
- Active front wheel steering

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-23-
**Maneuver sine with dwell**

<table>
<thead>
<tr>
<th>Driver</th>
<th>objective, no driver influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>80 km/h</td>
</tr>
<tr>
<td>Steering wheel angle input</td>
<td>single sine of 0.7 Hz with dwell of 500 ms after ( \frac{3}{4} ) of period, steady-state lateral acceleration of amplitude is 0.4 g</td>
</tr>
<tr>
<td>Road surface</td>
<td>dry, ( \mu = 0.9 )</td>
</tr>
</tbody>
</table>
Sine with dwell: Simulation results

Steering wheel angle input

<table>
<thead>
<tr>
<th>Steering wheel angle [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-10</td>
</tr>
<tr>
<td>-20</td>
</tr>
<tr>
<td>-30</td>
</tr>
<tr>
<td>-40</td>
</tr>
<tr>
<td>-50</td>
</tr>
</tbody>
</table>

Time [s]

0 1 2 3 4 5 6 7

Track

<table>
<thead>
<tr>
<th>Lateral position [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-2</td>
</tr>
<tr>
<td>-4</td>
</tr>
<tr>
<td>-6</td>
</tr>
<tr>
<td>-8</td>
</tr>
<tr>
<td>-10</td>
</tr>
</tbody>
</table>

Longitudinal position [m]

0 20 40 60 80 100 120 140 160

- Without control
- Active rear wheel steering
- Active front wheel steering

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-25-
Sine with dwell: Simulation results
Sine with dwell: Simulation results

Active rear wheel steering seems advantageous
**Sine with dwell on slippery road**

<table>
<thead>
<tr>
<th><strong>Driver</strong></th>
<th>objective, no driver influence</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Velocity</strong></td>
<td>80 km/h</td>
</tr>
<tr>
<td><strong>Steering wheel angle input</strong></td>
<td>single sine of 0.7 Hz with dwell of 500 ms after (\frac{3}{4}) of period, steady-state lateral acceleration of amplitude is 0.4 g (for vehicle without control)</td>
</tr>
<tr>
<td><strong>Road surface</strong></td>
<td>slippery, (\mu = 0.35)</td>
</tr>
</tbody>
</table>
Sine with dwell on low μ: Simulation results

<table>
<thead>
<tr>
<th>Steering wheel angle input</th>
<th>Track</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steering wheel angle [deg]</strong></td>
<td><strong>Latitudinal position [m]</strong></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-5</td>
</tr>
<tr>
<td>4</td>
<td>-10</td>
</tr>
<tr>
<td>5</td>
<td>-15</td>
</tr>
<tr>
<td>6</td>
<td>-20</td>
</tr>
<tr>
<td>7</td>
<td>-25</td>
</tr>
</tbody>
</table>

- Black: Without control
- Red: Active rear wheel steering
- Blue: Active front wheel steering
Sine with dwell on low $\mu$: Simulation results

![Graphs showing simulation results with and without control, comparing active rear wheel steering and active front wheel steering.]
Sine with dwell on low $\mu$: Simulation results

Active steering makes this maneuver driveable, rear wheel steering is most effective.
**Maneuver slalom**

<table>
<thead>
<tr>
<th>driver</th>
<th>Simpack driver model, driver influence</th>
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</thead>
<tbody>
<tr>
<td>velocity</td>
<td>90 km/h</td>
</tr>
<tr>
<td>front wheel steering angle</td>
<td>closed loop, by driver</td>
</tr>
<tr>
<td>road surface</td>
<td>dry, $\mu = 0.9$</td>
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</table>

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### Slalom: Simulation results

<table>
<thead>
<tr>
<th>Track</th>
<th>Steering wheel angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without control</td>
<td>Without control</td>
</tr>
<tr>
<td>Active rear wheel steering</td>
<td>Active rear wheel steering</td>
</tr>
<tr>
<td>Active front wheel steering</td>
<td>Active front wheel steering</td>
</tr>
</tbody>
</table>

**Graph 1:**
- **Lateral position [m]**
  - Y-axis range: -1.0 to 3.5
  - X-axis range: 0 to 500

**Graph 2:**
- **Steering wheel angle [deg]**
  - Y-axis range: -150 to 150
  - X-axis range: 0.0 to 20.0

**Position in road direction [m]**
- Y-axis range: -1.0 to 3.5
- X-axis range: 0 to 500

**Time [s]**
- Y-axis range: -150 to 150
- X-axis range: 0.0 to 20.0
Slalom: Simulation results

Less oscillations
Slalom: Simulation results

Rear wheel steering is advantageous

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Conclusion and Outlook

- Validated mbs vehicle model as a basis
- Simple implementation of active steering systems by additional dofs: rear wheel steering, front wheel steering
- Co-Simulation of Simpack and Matlab/Simulink® for integration of control systems
- Systems work effectively, effects on vehicle dynamics can be studied, active rear wheel steering seems more powerful

- Optimization of both systems still needed (optimize control parameters, take side slip limit and wheel slip into account)
- Mechanical design of rear wheel steering and implementation of an actor model
- Implementation of a steering actor model in case of front wheel steering
Acknowledgment

The author would like to thank Yangfang Yu for doing a lot of excellent modeling and simulation work.