Energy efficient torque vectoring for electric vehicles with multiple drivetrains

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Overview

- Torque vectoring concept
- Case study vehicle and test results
- Energy efficient torque vectoring
  - Control allocation
  - Reference yaw rate
- Experimental tests
- Conclusions
Direct yaw moment aiming at achieving a reference yaw rate
Allows changing cornering response, i.e. the understeer characteristic
Case study vehicle
Case study vehicle (1)

Vehicle dimensions

- Wheelbase: 2.665 m
- Half-track: 0.808 m
- Wheel radius: 0.364 m

Drivetrain

- Switched reluctance motor, 1 per wheel
- Power: 75 kW (peak); 35 kW (cont.)
- Torque: 80 Nm nominal
- Gearbox ratio: 10.56:1

*M1…M4: motor; I1…I4: inverter; VCU: vehicle control unit (dSPACE)*
Modular control structure

Case study vehicle (2)

Reference generator

High-level controller

Control allocator

Driver

Layer 1

Layer 2

Layer 3

reference yaw rate ($r_{\text{ref}}$)

wheel torque demands $\tau_{d,i}$ to generate $F_{X,C}$ and $M_{Z,C}$

traction/braking force ($F_{X,C}$) and yaw moment demands ($M_{Z,C}$)

$r$

$a_x, a_y, V$

$r_{\text{ref}}$

$M_{Z,C}$

$F_{X,C}$

$\delta$

$p_a, p_b$

$\Theta$

$\tau_{d,i}$
How to minimise energy consumption?

Part 1 - Energy efficient control allocation
Control allocation

Basic concept

- Small steering angle approximation >> vehicle sides treated independently
- Side torque demand:

\[
\tau_{d,L} = \frac{1}{2} \left( F_{x,c} - \frac{M_{z,c}}{d} \right) R \\
\tau_{d,R} = \frac{1}{2} \left( F_{x,c} + \frac{M_{z,c}}{d} \right) R
\]

⇒ CA problem >> front to rear torque distribution

\[
F_{x,c} = \frac{1}{R} \left( \tau_{w,1} + \tau_{w,2} + \tau_{w,3} + \tau_{w,4} \right)
\]

\[
M_{z,c} = \frac{d}{R} \left( -\tau_{w,1} + \tau_{w,2} - \tau_{w,3} + \tau_{w,4} \right)
\]

d: half track width
R: radius of wheel
Optimal front-to-rear torque distribution (1)

Energy efficient control allocation – investigation

**Drivetrain power losses**
(incl. inverter, motor, gearbox, CV-joints, tyre)

- Non-convex
- Convex
Optimal front-to-rear torque distribution (2)

Measured efficiencies on one vehicle side

Due to power loss characteristics:
- Low torque demands >> only front/rear
- High torque demands >> even distribution

⇒ ‘Switching torque’ based on torque and speed can be defined to obtain optimal solution
Optimal front-to-rear torque distribution (3)

Energy efficient control allocation – validation on roller test bench

### Switching torque

- **Switching torque (Nm)**
  - **Speed (km/h)**: 0, 20, 40, 60, 80, 100, 120, 140
  - **Switching torque values**:
    - 650 Nm
    - 600 Nm
    - 550 Nm
    - 500 Nm
    - 450 Nm
    - 400 Nm
    - 350 Nm
    - 300 Nm
    - 250 Nm

### Surrey Designed Driving Cycle

- **Speed (km/h)**: 0, 20, 40, 60, 80, 100, 150, 200
- **Time (s)**: 0, 50, 100, 150, 200

### Energy Consumption (kWh)

<table>
<thead>
<tr>
<th>Driving cycle</th>
<th>Energy consumption (kWh)</th>
<th>CA w.r.t.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SA</td>
<td>ED</td>
</tr>
<tr>
<td>NEDC</td>
<td>2.932</td>
<td>3.031</td>
</tr>
<tr>
<td>EUDC, 8% slope</td>
<td>5.838</td>
<td>5.739</td>
</tr>
<tr>
<td>SDDC</td>
<td>1.136</td>
<td>1.141</td>
</tr>
</tbody>
</table>
Optimal front-to-rear torque distribution (4)

Energy efficient control allocation - validation on proving ground

radius 60 m, speed 79 km/h, ~8 m/s²; switching torque: 335 Nm

<table>
<thead>
<tr>
<th></th>
<th>$P_{in}$ [kW]</th>
<th>Wheel torque demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>left [Nm]</td>
</tr>
<tr>
<td>SA</td>
<td>54.46</td>
<td>179.1</td>
</tr>
<tr>
<td>ED</td>
<td>54.22</td>
<td>175.5</td>
</tr>
<tr>
<td>CA</td>
<td>53.15</td>
<td>158.9 (SA)</td>
</tr>
</tbody>
</table>

energy savings ~2.5% [other tests ~4%]

three-wheeler!
How to minimise energy consumption?

Part 2 - Energy efficient understeer characteristics
Optimal reference understeer characteristics (1)

Designed cornering behaviour

Driving modes (e.g., Sport, Normal) selectable by driver >> Vehicle response ‘designed’ through torque vectoring controller

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**Graph:**
- **Axes:**
  - **a_y [m/s²]** (x-axis)
  - **δ_sw [deg]** (y-axis)
- **Lines/Markers:**
  - Sport
  - Normal
  - Passive
- **Annotations:**
  - **Extension of the linear region (Sport mode)**
  - **Increased maximum lateral acceleration**
  - **Variation of the understeer gradient**

**Image:**
- **Caption:** Skid pad test results (30 m radius, Lommel proving ground)
Optimal reference understeer characteristics (2)

Energy efficient reference yaw rate – investigation

Steady-state simulation - speed: 70 km/h; long. acc.: 0.5g; lat. acc.: 0.5g

**Lateral tyre slip power losses**

**Longitudinal tyre slip power losses**

Controlled vehicle

Passive vehicle

stabilising  destabilising

stabilising  destabilising
Optimal reference understeer characteristics (3)

Steady-state simulation - speed: 40 km/h; long. acc.: 0g; lat. acc.: 0.2g

Overall power input: drivetrains + tyres

- Drivetrains have nearly symmetric power loss behaviour in cornering
- Tyre slip power losses cause asymmetry

Optimal yaw moment destabilising
Extensive testing – 60m radius, lat. acc.: ~2, 4, 6, 8 m/s²

…with 11 understeer configurations
Optimal reference understeer characteristics (5)

Energy efficient reference yaw rate – experimental evidence

O1…O5: progressively less understeer configurations
U1…U5: progressively more understeer configurations
Optimal reference understeer characteristics (6)

Power losses during cornering

Relative power input increase (%)

- Passive vehicle
- Optimum UG characteristic

Energy savings ~11%
Optimal reference understeer characteristics (7)

Power losses during cornering

Relative power input increase (%)

\[ \text{Relative power input increase } (\%) \]

\[ \begin{array}{cccc}
17 & 13 & 9 & 5 \\
\end{array} \]

\[ P \]

\[ a_y = \text{constant} \]

\[ M_{zc} \]

\[ \text{Yaw moment (kNm)} \]

\[ \text{Lateral acceleration (m/s}^2) \]

- Passive vehicle
- Optimum UG characteristic
Torque vectoring control is effective in improving energy efficiency by reducing power losses associated with drivetrains and tyres.

Energy efficient CA algorithm energy savings between 2% and 3% (driving cycles) and up to ~4% during cornering conditions with respect to fixed torque distribution strategies.

Energy efficient understeer characteristic is less understeering and close to the condition of neutral steering.

The energy efficient reference cornering response reduces measured input power by up to ~11%.

Conclusions

For the case study electric vehicle
References