Rolling resistance measurement on the road: A dream?

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• Motivation
• Introduction of the used Measurement Equipment
• Introduction of the theoretical approach
• Description of the Test procedure
• Results
• Summary / Conclusions
Motivation

• The demand to higher efficiency concerns each component of future vehicles
• Tire resistance is identified as one of the areas for efficiency improvements independent of vehicle drive concepts
• Understanding the behavior in real road conditions will become more important
• Standard testing methods (drum based) do not deliver road condition related information
• Real road conditions measurement was suffering from:
  – Accurate measurement equipment for the forces as Tire resistance value is relative low
  – Low repeatability
  – Ability to separate different influence sources
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Measurement Equipment on Road

- Vehicle measurement System (VMS)
  - Wheel Force Sensor (WFS)
  - Wheel Position Sensor (WPS)
  - Other sensors such as GPS
  - Vehicle ECU Information
• Flat belt tire testing rig (steel belt)
  – Best simulation of the road
• Test is performed with the same sensor used for the vehicle testing

<table>
<thead>
<tr>
<th>Rig Specification</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>0~200km/h</td>
</tr>
<tr>
<td>Slip Angle</td>
<td>±20deg (0~3Hz)</td>
</tr>
<tr>
<td>Camber Angle</td>
<td>±15deg (0~1Hz)</td>
</tr>
<tr>
<td>Up &amp; Down</td>
<td>0<del>50mm (0</del>25Hz)</td>
</tr>
<tr>
<td>Load</td>
<td>Fx: ±10 kN</td>
</tr>
<tr>
<td></td>
<td>Fy: ±10 kN</td>
</tr>
<tr>
<td></td>
<td>Fz: 12 kN</td>
</tr>
<tr>
<td>Flatness of the steel</td>
<td>Less than 10 μm</td>
</tr>
<tr>
<td>belt (under load condition)</td>
<td></td>
</tr>
<tr>
<td>Bearing under the belt</td>
<td>Air bearing</td>
</tr>
</tbody>
</table>
Wheel Force Sensor (WFS)

6 component in wheel force sensor main properties
- 3 axis of force and 3 axis of moment
- Total error 0.1%
- Capacity:
  - Fx = 24KN, Fy = 15KN, Fz = 24KN
  - Mx = 4.5 KNm, My = 4 KNm, Mz = 4.5 KNm
- Resolution 1/4000
  - 6N or 1.8Nm
- Data acquisition up to 1kHz
- Lightweight 3.2 Kg
Unique Force Detection Method

- Model Based Sensor concept
  - Shared force detection method
  - Eight bridges are applied to the spring element
  - No direct detection of each component
  - Components are re-composed by model based calculation using real time calculation DSP platform
  - Digital conversion of all signals and electronically re-composing overcomes disadvantages of analogue approach
  - Cross talk error can be canceled out
Minimized Temperature effects

- Vehicle measurement is a challenge for the temperature influence
  - Temperature gradient e.g. break side outside
  - Quick change of temperature depending on driving maneuver
- Need for robust design against Temperature effects
  - Share Force method allows to place the strain gauges very close to each other
  - Total gradient on each gauge is very small
  - Small temperature effect on the measurement
  - At the same time robustness against dynamic temperature changes
Mechanical and Electrical sensitivity

- Application needs stiff sensor and high accuracy
- Sensor sensitivity:
  - Mechanical sensitivity x electrical sensitivity
- Stiff Spring element design results in:
  - Increase of robustness
  - Increase of eigenfrequency
  - Reduction of mechanical sensitivity
- Increase electrical sensitivity by utilizing:
  - High precision A/D converting of nV order
  - Low noise design from less analog circuit
  - Optimized temperature compensation from gauge layout
- The combination of all technology results in a high accurate sensor with 1/4000 resolution
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**Tire Loss Theory**

- Tire loss can be calculated from measured parameters on the wheel

**Measurement parameters**
- Tire rolling inertia \( J_t \) in kg\( \cdot \)m\(^2\)
- Tire effective radius \( r_t \) in m
- Wheel torque \( M_y \) in Nm
- Tire longitudinal force \( F_x \) in N
- Tire Angular speed \( \omega \) in rad/s
- Tire Angular acceleration \( \dot{\omega} \) rad/s\(^2\)

**Calculated parameter**
- Tire loss (rolling resistance) \( R_x \) in N

\[
R_x = \frac{M_y + J_t \cdot \dot{\omega}}{r_t} - F_x
\]
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Testing procedure on the test track

- Target: Determine “Tire Loss” from real driving condition
- Test car: BMW Mini Cooper S
- Test Track:
  - Total length: 1,792m
  - East straight line: 550m
  - West straight line: 554m
- Driving Maneuver:
  - Acceleration at west straight line
  - Cost down at East straight line
  - Test laps: 10 laps
- 100Hz data acquisition
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Test Track Measurement Results

- Example plot of one round
- $F_x$ shows mainly difference between front and rear wheel
- $F_z$ shows change between left and right
Parameter Determination

Direct Measures from the sensor:
- Wheel torque $M_y$ in Nm
- Tire longitudinal force $F_x$ in N

Indirect Measures:
- Tire rolling inertia $J_t$ in kg$\cdot$m$^2$
- Tire effective radius $r_t$ in m
- Tire Angular acceleration $\dot{\omega}$ rad/s$^2$

$$R_x = \frac{M_y + J_t \cdot \dot{\omega}}{r_t} - F_x$$
Wheel inertia

- Tire rolling inertia is premeasured using free load rotating wheel in acceleration and deceleration condition

- Measurement items
  - Tire angular speed $\omega$ [rad/s]
  - Angular acceleration $\dot{\omega}$ [rad/s$^2$]
  - Wheel torque $My_{\text{free}}$ [Nm]

- Rolling inertia formula:
  $$J_t = \frac{My_{\text{free}}}{\dot{\omega}}$$
Angular acceleration determination

- Tire angular speed is measured from sensor angle encoder.
- Tire angular acceleration is calculated from angular speed signal by time derivative.
- Measurement item:
  - Tire angular speed $\omega$ [rad/s]
  - Tire angular acceleration $\dot{\omega} = \frac{d\omega}{dt}$
Tire radius determination

- Tire mean radius is calculated from vehicle velocity and tire angular speed.
- Vehicle velocity is measured from optical Doppler sensor
- Instant tire mean radius is measured.
- Measurement items
  - Vehicle velocity against road $V_{ph}$ [m/s]
  - Tire angular speed $\omega$ [rad/s]
- Tire radius formula
  (Not considering tire slip)
  $$R_t = \frac{V_{ph}}{\omega} \quad [m]$$
Measurement parameter: Wheel torque and longitudinal force

- Wheel torque $M_y$ and longitudinal force $F_x$ are measured from 6 components of the Wheel Force Sensor (WFS).
Rolling Resistance Results

• To avoid tire slip error, driven wheel data is evaluated

• 10 laps of data

• To avoid some high frequency noise a low pass filter (4 Hz) is applied to the measurement data

• Very good repeatability for 10 laps
Rear Left Wheel results

- Average Rx: Rx = -76.1N (Acceleration), Rx = -72.8N (Cost down)
- 10 laps data variation 3σ : 2.8N (Acceleration), 3.6N (Cost down)
- Rx for Acceleration and Rx for Cost down data are very close to each other: 3.3N
Rear Right Wheel results

- Average Rx: Rx = -87.6N (Acceleration). Rx = -82.6N (Cost down)
- 10 laps data variation 3σ: 2.5N (Acceleration), 6.6N (Cost down)
- Rx for Acceleration and Rx for Cost down data are very close to each other: 5.0N
Measurement result: Test rig

Test condition:
- Slip angle: 0 [deg]
- Camber angle: 0 [deg]
- Wheel driven by steel belt
- Vertical load Fz: 1kN, 2kN, 5kN
- Static velocity: 5km/h, 10km/h, 20km/h, 60km/h, 80km/h, 120km/h

- Rolling resistance is directly measured from Fx using same sensor as on the road

Results:
- Rolling resistance is proportional to the vertical load and is not a function of velocity
- Rolling resistance at 2.7kN is 42N
Comparison: Real road vs Test rig

Real road rolling resistance:
• Rx(Left) = 74 N
• Rx(Right) = 82 N

Test rig:
• Rx = 42 N

Reasons for the difference:
• Tire alignment on Road and rig is different
• Road surface condition
• Environment conditions
  – Wind force to tire
  – Temperature
• Measurement errors
  – Tire effective radius measurement
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Summary:

• A&D Sensor delivers high quality data
  • Repeatability of 10 lab data did show good match
• It was possible to measure the tire loss (rolling resistance) during real driving condition
• Great match on the results though 10 laps of data
• Rolling resistance measurement result is depending on driving conditions
  • We did observer difference between acceleration and coast down conditions
• There are differences between road and test rig results

Conclusion:

• WFS is a useful tool for analyzing energy loss at real driving condition
• We are very close to the dream and will continue this investigation
Thank you for your attention!

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