Comparison of Braking Performance by Electro-Hydraulic ABS and Motor Torque Control for In-wheel Electric Vehicle

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Introduction
- In-wheel electric vehicle

- Equips drive motor to each wheel with brake and suspension systems
- Propels the vehicle **only by the electric energy** using in-wheel independent motors
Introduction
- Advantages

✓ No transmission, engine, shaft and axle
✓ More space
✓ Independent control of each wheel (Extended vehicle control area)
Introduction
- Advantages

✓ High power transmission efficiency

✓ Improved fuel economy by regenerative braking at each wheel

In-wheel system

✓ Possibilities of application on various x-EVs platforms
Purpose of study

- Develop an in-wheel motor torque control algorithm
  - Slip control based on $\mu$ and $\lambda$

- Develop ABS experiment environment and ABS simulator

- Develop CarSim-MATLAB/Simulink co-simulator

- Compare the braking performance of in-wheel motor torque control with that of ABS
In-wheel motor torque control
- Structure of in-wheel electric vehicle

- Sprung mass : 1700 kg
- Front in-wheel motor power : 35 kW
  reduction gear ratio : 8.45
  maximum torque : 75 Nm
  maximum speed : 11000 rpm
- Rear in-wheel motor power : 16 kW
  reduction gear ratio : 4
  maximum torque : 123 Nm
  maximum speed : 5000 rpm
In-wheel motor torque control
- Estimated vertical force

< Vehicle dynamics model >

- Using equation (1), (2), (3), nomal forces at each wheel are obtained

$$\begin{align*}
F_{z,\beta} &= \frac{h\left(-\frac{1}{2} C_d AV_x^2 - mg \sin \beta - m\dot{V}_x\right) + b \cdot mg \cos \beta}{a + b} + \frac{h m a_y}{w} \\
F_{z,\delta} &= \frac{h\left(-\frac{1}{2} C_d AV_x^2 - mg \sin \beta - m\dot{V}_x\right) + a \cdot mg \cos \beta}{a + b} + \frac{h m a_y}{w} \\
F_{z,\psi} &= \frac{h\left(-\frac{1}{2} C_d AV_x^2 - mg \sin \beta - m\dot{V}_x\right) + b \cdot mg \cos \beta}{a + b} - \frac{h m a_y}{w} \\
F_{z,\epsilon} &= \frac{h\left(-\frac{1}{2} C_d AV_x^2 - mg \sin \beta - m\dot{V}_x\right) + a \cdot mg \cos \beta}{a + b} - \frac{h m a_y}{w}
\end{align*}$$
In-wheel motor torque control
- Motor torque control

- Feed forward term: \[ T_{x\_limit} = R \times F_{x\_limit} = R \times \mu F_z \]

- Feed back term: \[ T_{x\_limit} = K_{\text{slip control}} (\lambda_d - \lambda) \times (\lambda > \lambda_d) \]

- Limited motor torque: \[ T_{\text{limit}} = R F_{x\_limit} + K_{\text{slip control}} (\lambda_d - \lambda) \times (\lambda > \lambda_d) \]
ABS experiment and simulator
- Structure of ABS
ABS experiment and simulator

- ABS experiment environment

- ABS simulator

Verification!
ABS experiment and simulator
- Solenoid valve modeling

- Traction control valve (TCV) modeling

\[ P_{tcv} = \frac{K}{T_w(i_{tcv})^2 s^2 + T_w(i_{tcv})2 \zeta s + 1} e^{-\tau s i_{tcv}} \]

\[ P_{tcv\; init} = P_{line} \]

\[ T_w(i_{tcv}) = T_w + K_p i_{tcv}^3 \]

- Verification

< Step input >

< Ramp input >
ABS experiment and simulator
- Solenoid valve modeling

- Outlet valve (OV) modeling - on/off valve

\[ P_{ov} = \frac{K}{T_{ws} + 1} e^{-\tau s} i_{ov} \]

\[ P_{ov\_init} = P_{line} \]

- Verification

![Graph showing \( P_{\text{experiment}} \) and \( P_{\text{simulation}} \) over time for a step input.]
ABS experiment and simulator
- Mode 1 (default)
ABS experiment and simulator
- Mode2 (maintaining pressure)
ABS experiment and simulator
- Mode3 (decreasing pressure)
ABS experiment and simulator
- Mode4 (increasing pressure)
ABS experiment and simulator
- Mode control – MATLAB state flow

Mode1
During: \( P_{\text{out}} = P_{\text{line}} \),
\( P_{\text{previous}} = P_{\text{line}} \)

Mode2
Entry: \( P_{\text{out}} = P_{\text{previous}} \),
\( I_{ov} = 0 \),
\( I_{iv} = 100 \)

Mode3
During: \( P_{\text{out}} = P_{\text{ov}} \),
\( P_{\text{previous}} = P_{\text{ov}} \)

Mode4
During: \( P_{\text{out}} = P_{\text{iv}} \),
\( I_{ov} = 0 \),
\( I_{iv} < 100 \)

I_{ov} = 0 
I_{iv} = 100
ABS experiment and simulator
- ABS simulator
ABS experiment and simulator
- Experiment and simulation results

- $i_{TCV} = 1000 mA$
ABS experiment and simulator
- Experiment and simulation results

- $i_{TCV} = 1200\sim 800$ mA

![Graphs showing experimental and simulated results for Voltage, Current, TCV, FLIV, and FLRR over time.](image-url)
Simulation results
- MATLAB – CarSim co-simulator

< CarSim vehicle model >

< MATLAB/Simulink model >
Simulation results
- 60 kph full braking, $\mu = 0.2$

In-wheel motor torque control

- ABS

Vehicle velocity (km/h, front)

Vehicle velocity (km/h, rear)

Time (sec)
Simulation results
- 60 kph full braking, $\mu = 0.2$

- In-wheel motor torque control

- ABS

Motor torque (Nm)

Friction brake torque (Nm)

Deceleration (g)

Time (sec)

-0.4 0 10

-1000 0

0 0

-1500

0

-0.4

0 0

0 0

0 0

-0.4

0 0

0 0
Simulation results
- 60 kph full braking, $\mu = 0.2$

- In-wheel motor torque control

- ABS

Slip ratio range : 0 ~ 10% 
(V\geq10kph)
Slip ratio range : 0 ~ 20% 
(V<10kph)
Total braking distance : 64.1m

Slip ratio range : 0 ~ 25% 
(V\geq10kph)
Slip ratio range : 0 ~ 80% 
(V<10kph)
Total braking distance : 77.7m
Simulation results
- 60 kph full braking, $\mu = 0.4$

- In-wheel motor torque control

- ABS

Vehicle velocity (km/h, front) vs. Time (sec)
- $V$
- $V_{w_{fl}}$
- $V_{w_{fr}}$

Vehicle velocity (km/h, rear) vs. Time (sec)
- $V$
- $V_{w_{rl}}$
- $V_{w_{rr}}$
Simulation results

- In-wheel motor torque control

- ABS

Simulation results:
- 60 kph full braking, $\mu = 0.4$
Simulation results

- In-wheel motor torque control
  - 60 kph full braking, $\mu = 0.4$
  - Slip ratio range: $0 \sim 5\%$
  - Total braking distance: 47.1m
  - Insufficient motor torque!

- ABS
  - Slip ratio range: $0 \sim 25\%$
    (V$\geq$10kph)
  - Slip ratio range: $0 \sim 60\%$
    (V$<$10kph)
  - Total braking distance: 39.8m
Conclusions

- An in-wheel motor torque control algorithm was developed for an in-wheel electric vehicle.

- To implement the ABS operation environment, ABS simulator was developed based on the ABS test results.

- It was found from the simulation results (60kph full braking, $\mu=0.2$) that the in-wheel motor torque control showed better performance with a smaller slip ratio and a shorter braking distance compared with the ABS.

- The in-wheel motor torque control may have the problem of insufficient braking force due to the torque limit of the motor, which requires cooperative control with the friction brake.