Fault-tolerant Control System for EMB Equipped In-wheel Motor Vehicle

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Introduction

◆ Motivation
  ● Popularization of EVs
    – Increase in interest in fuel economy and regulation of the environment
    – Replace the ICE (Internal Combustion Engine) with the Electric Motor
    – In-Wheel Motor Vehicle is being studied
  ● Demand for the New Type of Brake System
    – The conventional hydraulic brake system equips the vacuum booster
    – EVs need new type of brake system because they have no ICE and vacuum booster.
      ▪ EMB (Electro-Mechanical Brake) System
        • Using the Electric Motor
        • Fast response and Less Weight
        • No environmental pollutant
      ▪ Re-generative Brake System
        • In EVs, the re-generative braking by drive motor is available
        • In In-wheel Motor Vehicle, independent braking of each wheel is available
Related Work: Component Level Fail-safe Approach

- Fault-tolerant control of EMB systems (Ki et al., SAE Int. J., 2012)
  - The fail-safe system utilizing the estimated signal when sensor failure was occurred
  - Sensor type: Current, Position, and Clamping force etc.
    - This research was focused on the component level fail-safe didn’t consider the system level fail-safe
Introduction

◆ Related Work: System Level Fail-safe Approach

● Control of brake- and steer-by-wire during brake actuator failure (Hac et al., SAE Technical Paper, 2006)

● Development of a fail-safe control strategy based on evaluation scenarios for an FCEV electronic brake system (Jeon et al., IJAT, 2012)
  - Simplified fault-tolerant control algorithm is used in these researches
Introduction

◆ Related Work: System Level Fail-safe Approach (Cont’d)

- Fault-tolerant control with active fault diagnosis for four-wheel independently driven electric ground vehicles (Wang et al., IEEE Transaction on Vehicular technology, 2010)
  - The active fault diagnosis is proposed to explicitly isolate the faulty EMB wheel and to estimate control gain of the faulty wheel
  - The adaptive control scheme is used for calculating the desired braking torque at each EMB
Introduction

◆ The Purpose of Fault-Tolerant System
  ● Minimize the Effect of Faulty EMBs
    – Compensation of Total Braking Force
      ▪ Increase the Braking Torques from No fault occurred EMB
    – Prevention of the Partial Brake
      ▪ Satisfy the Driver’s Braking and Steering Command
      ▪ Enhancement of the Vehicle Stability
  ● Consider the Limits of braking
    – Road-Tire Friction Limits
      ▪ Magnitude of generated tire force is decided by tire-road friction coefficient and vertical load
      ▪ Therefore, no matter how large clamping force is produced, there is limitation of generated braking force on each wheel
    – Brake Actuator Performance Limits
      ▪ Due to the limitations of the Actuator, the maximum braking force is determined.

: The Fault-tolerant system should be designed to consider the limits!
Fault-tolerant System Architecture

**System Architecture**
- **Vehicle Dynamics Controller (Sliding Mode Control)**
  - The required total braking force and moment is generated to fulfill the intend of the driver
- **Braking Force Distribution Logic (Optimization)**
  - Each braking force of EMB is calculated to track the desired braking force and moment at the same time satisfy the constraints

![Fault-tolerant System Architecture Diagram]
EMB (Electro-Mechanical Brake) Model

◆ Experiment & Fitting
  ● Input Current Vs. Clamping Force
    - The EMB has linearity between current input and clamping force
      \[ F_{i\_clp} = K_i \cdot u_i \]
    - The Braking force generated from EMB can be modelled as:
      \[ F_{i\_EMB} = \frac{2\mu_r F_{i\_clp}}{r_{eff}} = \frac{2\mu_r K_i u_i}{r_{eff}} \]
      \[ F_{i\_clp} : \text{EMB Clamping Force} \]
      \[ F_{i\_EMB} : \text{EMB Braking Force} \]
      \[ K_i : \text{EMB Linear Gain} \]
      \[ u_i : \text{Input Current} \]
      \[ \mu_r : \text{Friction Coefficient} \]
      \[ r_b : \text{Effective Brake Rotor Radius} \]
      \[ r_{eff} : \text{Effective Wheel Radius} \]
Re-generative Brake Model

◆ The Strategy of Regenerative Braking
  ● The maximum available regen. torque is determined depending on the speed of the vehicle
    – The maximum available regen. torque is depending on the speed of driving motor
  ● The regenerative torque varies depending on:
    – The SOC (State Of Charge) for managing the battery
    – The fault status of the EMB
    → The regen. torque is maximized when the fault on its EMB is occurred
Vehicle Dynamics Controller Design

◆ Driver Model
  ● Desired Longitudinal Speed
  \[ V_{x,\text{desired}} = V_0 + \int a_{x,\text{desired}} \, dt \]
  ● Desired Yaw Rate
  \[ \gamma_{\text{desired}} = \frac{V_x}{l_f + l_r} + \frac{mV_x^2 (l_r C_{ar} - l_f C_{af})}{2C_{af} C_{ar} (l_f + l_r)} \cdot \delta_{sw} \frac{GR}{2} \]

◆ Sliding Mode Controller Design
  ● Newton’s Law
  \[ m_v \dot{V}_x = F_x - F_{x,\text{disturbance}} \]
  \[ I_z \ddot{\gamma} = M_{cg} \]
  ● Control Law
  \[ F_{x,\text{desired}} = m_v \left( \dot{V}_{x,\text{desired}} + \eta_1 \text{sat}(S_1) \right) + F_{x,\text{disturbance}} \]
  \[ M_{cg,\text{desired}} = I_z \left( \dot{\gamma}_{\text{desired}} + \eta_2 \text{sat}(S_2) \right) \]
  ● Sliding Surface
  \[ S_1 = V_x - V_{xd} \]
  \[ S_2 = \gamma - \gamma_d \]
  \[ \dot{S}_1 = \dot{V}_x - \dot{V}_{xd} = -\eta_1 \text{sign}(S_1) \]
  \[ \dot{S}_2 = \dot{\gamma} - \dot{\gamma}_d = -\eta_2 \text{sign}(S_2) \]

\[ \text{sat} \left( \frac{S}{\phi} \right) = \begin{cases} \frac{S}{\phi}, & \text{if } |S| < \phi \\ \text{sign} \left( \frac{S}{\phi} \right), & \text{if } |S| \geq \phi \end{cases} \]
Braking Force Limit

◆ The limitations on the braking force

- The normal force acting on each wheel considering the acceleration

\[
N_{LF} = \frac{Mb}{2L} g - \frac{Mh}{2L} a_x + \frac{Mh}{t_w} a_y
\]

\[
N_{RF} = \frac{Mb}{2L} g - \frac{Mh}{2L} a_x - \frac{Mh}{t_w} a_y
\]

\[
N_{LR} = \frac{Ma}{2L} g + \frac{Mh}{2L} a_x + \frac{Mh}{t_w} a_y
\]

\[
N_{RR} = \frac{Ma}{2L} g + \frac{Mh}{2L} a_x - \frac{Mh}{t_w} a_y
\]

- Limits on the road friction coefficient

\[
F_{i,\text{RoadLimit}} = \mu_{\text{tire}} N_i
\]

- Limits on the EMB Actuator

\[
F_{i,\text{EMBLimit}} = \frac{2 \mu r_b K_i}{r_{\text{eff}}} u_{i,\text{max}}
\]

- The maximum braking force of each wheel

\[
F_{i,\text{max}} = \min \left( F_{i,\text{EMB Limit}} + F_{i,\text{Regen}}, F_{i,\text{Road Limit}} \right)
\]
2-D.O.F Vehicle Modeling

◆ Ratio of the Maximum Braking Force
  ● Maximize the stability of vehicle and margin of the actuator while braking

\[ F_i = \lambda_i \cdot F_{i,max} \]

◆ The Braking Force and Moments Acting on the Vehicle
  ● Summations of the braking forces on left and right side

\[ F_{x\_cg} = (F_{L1} + F_{L2}) + (F_{R1} + F_{R2}) \]
\[ M_{cg} = \frac{W}{2} \left( (F_{L1} + F_{L2}) - (F_{R1} + F_{R2}) \right) \]

\[
F_{x\_cg} = \frac{\lambda_L}{2} \left( \frac{F_{L1,max} + F_{L2,max}}{2} \right) + \frac{\lambda_R}{2} \left( \frac{F_{R1,max} + F_{R2,max}}{2} \right)
\]
\[
M_{cg} = \frac{\lambda_L}{2} \left( \frac{F_{L1,max} + F_{L2,max}}{2} \right) - \frac{\lambda_R}{2} \left( \frac{F_{R1,max} + F_{R2,max}}{2} \right) \cdot W
\]
Optimization Problem

◆ Object Function

\[ J = W_{F_x} \left[ F_{x,desired} - \left\{ \lambda_L (F_{L1,\text{max}} + F_{L2,\text{max}}) + \lambda_R (F_{R1,\text{max}} + F_{R2,\text{max}}) \right\} \right]^2 \]

\[ + W_{M_{cg}} \left[ M_{cg,desired} - \frac{W}{2} \left\{ \lambda_L (F_{L1,\text{max}} + F_{L2,\text{max}}) - \lambda_R (F_{R1,\text{max}} + F_{R2,\text{max}}) \right\} \right]^2 \]

◆ Constraints

\[ 0 \leq \lambda_L \leq 1 \]
\[ 0 \leq \lambda_R \leq 1 \]

\[ g1: -\lambda_L \leq 0 \]
\[ g2: \lambda_L \leq 1 \]
\[ g3: -\lambda_R \leq 0 \]
\[ g4: \lambda_R \leq 1 \]

◆ Formulation of the Lagrange Function

\[ L = J + \sum u_i \left( g_i + s_i^2 \right) \]

◆ KKT(Karush-Kuhn-Tucker) Necessary Condition is satisfied

◆ Sufficient condition: \[ H = \nabla^2 J \]

\[ \det (H) = 4W_{F_x} W_{M_{cg}} w^2 (F_{L1,\text{max}} + F_{L2,\text{max}})^2 (F_{R1,\text{max}} + F_{R2,\text{max}})^2 > 0 \]
Simulation Configuration

◆ Simulation Tools
  ● MATLAB/Simulink & CarSim

◆ Simulation Scenarios
  ● Friction coefficient of the road: 0.85
  ● Steering input: Double Lane Change
  ● Speed range: 120 km/h ~ 0 km/h

◆ Vehicle Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curb weight</td>
<td>M 1872.0000</td>
</tr>
<tr>
<td></td>
<td>Mf 1140.0000</td>
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<tr>
<td></td>
<td>Mr 732.0000</td>
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<tr>
<td>Effective radius of the wheel</td>
<td>r_w 0.3280</td>
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<tr>
<td>Wheel base</td>
<td>L 2.6400</td>
</tr>
<tr>
<td>Dist. of F wheel to CG point</td>
<td>Lf 1.0323</td>
</tr>
<tr>
<td>Dist. of R wheel to CG point</td>
<td>Lr 1.6077</td>
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<tr>
<td>Height of the CG point</td>
<td>h 0.5544</td>
</tr>
<tr>
<td>Effective radius of front disk</td>
<td>radius_eff_front 0.1114</td>
</tr>
<tr>
<td>Effective radius of rear disk</td>
<td>radius_eff_rear 0.1130</td>
</tr>
<tr>
<td>Front brake pad friction coefficient</td>
<td>U_pad_front 0.3400</td>
</tr>
<tr>
<td>Rear brake pad friction coefficient</td>
<td>U_pad_rear 0.3400</td>
</tr>
</tbody>
</table>
Simulation Results

- No faults on any EMB (0.3g Command w/o Re-generative Brake)
  - Algorithm based on the Look-up table vs. proposed method
Simulation Results

- No faults on any EMB (0.3g Command w/o Re-generative Brake)
  - Algorithm based on the Look-up table

- Algorithm based on the proposed method
Simulation Results

- Fault occurred on the Front-Left EMB (0.3g Command w/o Re-generative Brake)
- Algorithm based on the Look-up table vs. proposed method
Simulation Results

- Fault occurred on the Front-Left EMB (0.3g Command w/o Re-generative Brake)
  - Algorithm based on the Look-up table
  - Algorithm based on the proposed method
Simulation Results

- **Fault occurred on the Front-Left EMB (1.0g Command w/ Re-generative Brake)**
  - **Braking performance**: The braking command of 1.0g is not satisfied (0.5g approx.)
  - **Stability performance**: The steering stability is satisfied while on braking
Conclusions

◆ Fault Tolerant Algorithm Design
  ● The fault tolerant algorithm is designed to minimize the effect of the faults
    – Compensation of the lack of the total braking force
    – Prevent losing stability due to the differential braking
  ● The braking force re-distribution logic is designed considering the limitation of braking force
    – The limitations of the friction coefficient between the road and tire is considered
    – The performance limitations on actuators are considered

◆ Validation
  ● Simulations with the commercial software, the MATLAB/Simulink and CarSim
    – Effects of the faults on EMB are evaluated
    – The proposed algorithm in this research is validated