Iterative Learning Control of Antilock Braking of Electric and Hybrid Vehicles

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Outline

• Introduction - Overview of HEV
• Part I – Iterative Learning Control
• Part II – Antilock Braking
  • Vehicle Model
  • Slip Ratio Model
  • The Learning Process
  • Required Braking torque
• Simulation Examples
• To Probe Further
What is HEV

• HEV – Stands for Hybrid Electric Vehicle
• An HEV is a vehicle which involves multiple sources of propulsions
  – An EV is an electric vehicle, battery (or ultra capacitor, fly wheels) operated only. Sole propulsion by electric motor
  – A fuel cell vehicle is a series hybrid vehicle
  – A traditional vehicle has sole propulsion by ICE or diesel engine
• Therefore, HEV is essentially different from traditional vehicle

Types of HEV

• Parallel HEV: multiple propulsion sources combined
• Series HEV: sole propulsion by electric motor, but the electric energy comes from another on board energy source, such as ICE
• Fuel Cell Vehicle (FCEV), use fuel cell as energy source, it is a series HEV
Why HEV?

To Overcome the Disadvantage of Pure EV and Conventional Vehicles
Key Drawbacks of EVs

• High Initial Cost
  – Many times that of conventional vehicles

• Short Driving Range
  – Less miles during each recharge
  – People need a vehicle not only for commuting (city driving), but also for pleasure (long distance highway driving)

• Recharging takes much longer time than refueling gasoline.
Key Advantage of HEV

• Optimize the fuel economy
  – Optimize the operating point of ICE
  – Stop the ICE if not needed
  – Recover the kinetic energy at braking
  – Reduce the sizes of ICE

• Reduce emissions
  – Minimize the emissions when ICE is in operation
  – Stop the ICE when it’s not needed
  – Reduced size of ICE means less emissions

• FCEV does not have emission
Energy Optimization

Operating area of non-hybrid system

Efficiency

Output Power

Fuel Cell

Operating area of hybrid system

Performance

- **Quiet Operation**
  - *There is no noise at low speed because ICE is stopped*
  - *Quiet motor, motor is stopped when vehicle comes to a stop*

- **Reduced maintenance because ICE operation is optimized, which means**
  - *Less tune ups, longer life cycle of ICE*
  - *Less spark-plug changes*
  - *Less oil change*
  - *Less fuel filters, antifreeze, radiator flushes or water pumps*
  - *Less exhaust repairs or muffler changes*
History of Electric Vehicles

- EVs were invented in the 19th century
- Vanished since 1930 due to range, price, and reliability
- Resumed in 1976 because oil crisis
- Has been very active over the world
- Have introduced different types of HEVs
- Have commercialized vehicles

A Comparison of EV, HEV and FCEV

<table>
<thead>
<tr>
<th>Types of EVs</th>
<th>Battery EVs</th>
<th>Hybrid EVs</th>
<th>Fuel Cell EVs</th>
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<tbody>
<tr>
<td>Propulsion</td>
<td>Electric motor drives</td>
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<td>Battery</td>
<td>Electric grid charging facilities</td>
<td>Electric grid charging facilities (optional)</td>
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<td>Ultracapacitor</td>
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<td>Energy source &amp; infrastructure</td>
<td>Electric grid charging facilities</td>
<td>Gasoline stations</td>
<td>Hydrogen</td>
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<td></td>
<td></td>
<td>Electric grid charging facilities (optional)</td>
<td>Methanol or gasoline</td>
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<tr>
<td>Characteristics</td>
<td>Zero emission</td>
<td>Very low emission</td>
<td>Zero emission or ultra low emission</td>
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<tr>
<td></td>
<td>Independence on crude oils</td>
<td>Long driving range</td>
<td>High energy efficiency</td>
</tr>
<tr>
<td></td>
<td>100-200 km, short range</td>
<td>Dependence on crude oils</td>
<td>Independence on crude oils</td>
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<tr>
<td></td>
<td>High initial cost</td>
<td>Complex</td>
<td>Satisfied driving range</td>
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<td>Commercially available</td>
<td>High cost now</td>
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<tr>
<td>Major issues</td>
<td>Battery and battery management</td>
<td>Managing multiple energy sources</td>
<td>Fuel cell cost</td>
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<td></td>
<td>High performance propulsion</td>
<td>Dependent on driving cycle</td>
<td>Fuel processor</td>
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<td>Charging facilities</td>
<td>Battery sizing and management</td>
<td>Fueling system</td>
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Development Trends

Key Data of Current EVs

<table>
<thead>
<tr>
<th>EVs</th>
<th>Batteries</th>
<th>Driving Range (km)</th>
<th>Weight (kg)</th>
<th>Battery Weights (kg)</th>
<th>Price (US$)</th>
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<td>Curb</td>
<td>Passenger</td>
<td>Sale/Rent</td>
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<td>PbA</td>
<td>88-152</td>
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<td>553</td>
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<tr>
<td></td>
<td>NiMH</td>
<td>126-208</td>
<td>1205</td>
<td>2</td>
<td>410</td>
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<tr>
<td>GM S-10</td>
<td>PbA</td>
<td>64-88</td>
<td>1977</td>
<td>2.564kg</td>
<td>612</td>
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<tr>
<td></td>
<td>NiMH</td>
<td>104-128</td>
<td>1909</td>
<td>2.437kg</td>
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<tr>
<td>Ford Ranger EV</td>
<td>PbA</td>
<td>80</td>
<td>2243</td>
<td>2.595kg</td>
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<td>NiMH</td>
<td>104-136</td>
<td>1907</td>
<td>2.568kg</td>
<td>N/A</td>
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<tr>
<td>Toyota RAV4</td>
<td>NiMH</td>
<td>202</td>
<td>1564</td>
<td>5.376kg</td>
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<td>GM S-10</td>
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Overview of the Toyota Prius

Toyota Prius (1997)
The 2003 Prius Model

How far will you go to save the planet? About 566 miles per tank.

Inside

Note: radio controls in touch-screen.


Trunk Space

Planetary Gear

Planetary gear set (power split device)

- Four-cylinder engine
- Drive train
- Ring gear (motor and output axle)
- Sun gear (generator)
- Planetary carrier (engine)
• Starting and low speeds (up to 20mph)
  – ICE off
  – Motor drive the vehicle
  – Battery supply the needed power

• Sudden Acceleration
Power Flow

• Normal Driving
  – ICE power is split

• Braking
  – ICE is off
Specifications

- **Gas engine:**
  - Inline 4-cylinder DOHC, Displacement: 1,497 cc, Compression Ratio: 13.0:1
  - Peak Horsepower: 70 hp at 4,500 rpm
  - Peak Torque: 82 lb.-ft. at 4,200 rpm
  - Fuel Tank Capacity: 11.9 Gal.

- **ELECTRIC MOTOR –**
  - Permanent Magnet, Capacity: 6.5 amperes,
  - Peak Torque: 258 lb./ft. (350.0 Nm) 0-400 rpm,
  - maximum power of 33 kW (44 horsepower) from 1,040-5,600 rpm, and maximum torque of 350 N·m (258 lb./ft.) from 0-400 rpm.
Specifications

• ELECTRIC GENERATOR –
  – Permanent Magnet, Capacity: 15kW, peak efficiency 84%, 33kg, max current 300A

• BATTERY PACK
  – Peak Horsepower: 25 kW (34 hp)
  – Nominal Voltage: 274 volts

Specifications – Cont.

• EXTERIOR DIMENSIONS
  – Length: 169.6 in.
  – Width: 66.7 in.
  – Height: 57.6 in.
  – Wheelbase: 100.4 in.
  – Weight: 2,765 lb.
  – Seating Capacity: 5
Specifications – Cont.

• **INTERIOR DIMENSIONS**
  - Headroom (front/rear): 38.8 / 37.1 in.
  - Legroom (front/rear): 41.2 / 35.4 in.
  - Shoulder room (front/rear): 52.8 / 52.2 in.
  - Hip room (front/rear): 50.7 / 51.9 in.
  - Passenger volume: 88.6 cu. ft.
  - Cargo volume: 11.8 cu. ft.
  - Total interior volume: 100.4 cu. ft.
  - EPA class: Compact

Specifications – Cont.

• **Transmission**: Electrically Controlled CVT
• **Braking**: Front ventilated disc/Rear drum (Hydraulic, with Power Assist) with Integrated Regenerative Brake System
• **Steering**: Rack and Pinion
  Suspension (front/rear): MacPherson strut / Torsion beam
Range/MPG/Emission

- **Range:**
  - **11.9 gallon tank allows +500 miles between refills**
- **MPG:**
  - City (EPA rating)
  - 45 Highway (EPA rating)
- **Emission:** SULEV (Super Ultra Low Emission Vehicle)
  - 90% less NOx (Nitrogen Oxide)
  - 50% less CO2 (Carbon Dioxide)

The 2004 Prius Model

Over 11,000 vehicles has been sold, with initial estimation of 3000 vehicles

**MSRP:** $19,995
The 2004 Prius Model

- **Range:**
  - *15 gallon tank allows +500 miles between refills*
- **MPG:** 60
  - *City (EPA rating)*
  - *51 Highway (EPA rating)*
- **Emission:** SULEV (Super Ultra Low Emission Vehicle)

The future

- **A few new models coming out**
- **Toyota is planning to manufacture and market its hybrid vehicle in the US and China**
- **To increase annually to 300,000 per year to 2006**
Introduction

• HEV offers remarkable fuel savings and emission reduction
  – Toyota Prius: 60 MPG city driving
  – Toyota Corolla: 30 MPG
• Past studies was focused on modeling of HEV
• The multiple sources of power in HEV offers great ease and flexibility to achieve advanced control and additional driving performance

Introduction – Continued

• Advanced features of modern vehicles include antilock braking system (ABS) and traction control (TC)
• ABS and TC may not be effective due to the nonlinear characteristics and unknown environmental parameters.
• Advanced control algorithms, such as fuzzy control and neural network have been used to achieve antilock braking for conventional vehicles
**Introduction – continued**

- In addition to the primary function of propulsion, the electric motor can also be used effectively as the braking device
  - fast torque response characteristics
  - capability of regeneration.
  - The fast torque response provides the possibility to improve the vehicle antilock braking performance through the control of motor torque, without conventional ABS

**Part I: Iterative learning Control**
What is ILC

- **Iterative learning control (ILC)**
  - Proven to be effective for controls related to nonlinear dynamic systems
  - In this study, ILC was proposed to control the antilock braking of EV and HEV, using the electric motor to provide the required braking torque.

Iterative Learning Control

- Given a non-Linear dynamic process, find the input $u(t)$ function so that the output of the system $y(t)$ closely follows the desired output $y_d(t)$

\[ u(t) \rightarrow \text{Process} \rightarrow y(t) \rightarrow y_d(t) \rightarrow \text{Desired output} \rightarrow \text{Error} \rightarrow 0 \]
Example 1

\[
\begin{align*}
\dot{x}_1(t) &= (\sin x_1 + 2 \sin x_2) \frac{1}{1+t} + 3t \cdot u(t) \\
\dot{x}_2(t) &= 0.3 \sin x_1 + \frac{\sin x_2}{1+t} \cdot u(t) \\
y(t) &= \sin x_1 + 0.5 \sin x_2 + 0.5 \cdot u(t) \\
x_1(t) &= 0.9 \\
x_2(t) &= 0.9
\end{align*}
\]

Desire that \(y(t)\) follows \(\sin(t)\)

Ex. 1 Continued

• If we choose \(u(t)\) as a step function, then the output is as follows:
Ex. 1 Continued

• If we choose \( u(t) \) as a sine function, then the output is as follows:

Using ILC

\[
\begin{align*}
    u_{k+1}(t) &= u_k(t) + \Gamma \frac{de_{k+1}(t)}{dt} + \Gamma_p e_{k+1}(t)
\end{align*}
\]
The output

The Input $u(t)$
After 3 steps of learning

The Model of Ex.1
The leaning process

- \( u(t+1) \) is based on \( u(t) \)
- \( u_{k+1}(t) \) is based on \( u_k(t) \)
- There have to be an optimum learning ratio
- There have to be a convergence problem
  - Refer to references in “probe further” section

Example II

\[
\begin{bmatrix}
\dot{x}_1(t) \\
\dot{x}_2(t)
\end{bmatrix} =
\begin{bmatrix}
0 & 1 \\
-2-5t & -3-2t
\end{bmatrix}
\begin{bmatrix}
x_1(t) \\
x_2(t)
\end{bmatrix} + \begin{bmatrix}
0 \\
1
\end{bmatrix} u(t)
\]

\( y(t) = x_2(t) \)
\( y_d(t) = 12t^2(1-t) \)
The model

The desired $y_d(t)$ and actual output $y(t)$

After Learning
After Learning the input \( u(t) \)

Break – Demonstration of the two examples
Part II: Antilock Braking

Vehicle Model

\[ \lambda = \frac{V \omega - V}{V} \]

\[ M \frac{dV}{dt} = -F_d(\lambda) \]

\[ F_d(\lambda) = \mu(\lambda) Mg \]

\[ J_\omega \frac{d\omega}{dt} = -T_m + rF_d(\lambda) \]
Vehicle Model

\[ \lambda = \frac{V - V}{V} \]

- Slip ratio – control variable
- Slip ratio is a function of vehicle speed and wheel speed

\[ M \frac{dV}{dt} = -F_d(\lambda) \]

- Vehicle speed is a function of braking force \( F_d \)
- Wheel speed is a function of braking torque \( T_m \) and braking force \( F_d \)
- \( F_d \) is unknown, but related to slip ratio

\[ J \frac{d\omega}{dt} = -T_m + rF_d(\lambda) \]

Typical Adhesive Coefficient

- For almost all road conditions, braking force reaches maximum around 0.15-0.20 slip ratio.
- We need to control the braking torque so that slip ratio is maintain at optimum, therefore, maximum braking effect can be achieved.
**Slip Ratio Model**

\[ \lambda = \frac{V_\omega - V}{V} \]

\[ \dot{\lambda} = -\frac{1}{V} \ddot{V}_\omega + \frac{V_\omega}{V^2} \dot{V} \]

\[ = -(1 + \lambda) \frac{\dot{V}}{V} + \frac{1}{V} \dot{V}_\omega \]

- We need to develop the state space equations of the vehicle system so that we can apply an algorithm
- Output-slip ratio
- Input-motor torque
- Example is shown to derive the slip ratio model

---

**State Space Function**

- Let
  \[ \begin{align*}
  x_1(t) &= \lambda \\
  \dot{x}_1(t) &= \dot{\lambda} \\
  x_2(t) &= V \\
  \dot{x}_2(t) &= -g\mu(x_1)
  \end{align*} \]

- Then
  \[ \begin{align*}
  \dot{x}_1(t) &= (1 + x_1(t)) \frac{g\mu(x_1)}{x_2(t)} + \frac{r^2Mg\mu(x_1)}{x_2(t)J_\omega} - \frac{r}{x_2(t)J_\omega} T_m(t) \\
  \dot{x}_2(t) &= -g\mu(x_1)
  \end{align*} \]
State Space Function

• Define motor torque as a function of vehicle speed

\[ T_m(t) = x_2(t)u(t) \]

• Then

\[
\begin{aligned}
\dot{x}_1(t) &= (1 + x_1(t)) \frac{g\mu(x_1)}{x_2(t)} + \frac{r^2 M\mu(x_1)}{x_2(t)J_\omega} - \frac{r}{J_\omega}u(t) \\
\dot{x}_2(t) &= -g\mu(x_1)
\end{aligned}
\]

The Output

• The output is defined as the slip ratio

\[ Y(t) = [1, 0] \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} \]
State Space Function

\[
\begin{align*}
\dot{X}(t) &= f(X(t), t) + B(X(t), t)u(t) \\
Y(t) &= C(t)X(t)
\end{align*}
\]

\[
X(t) = [x_1(t), x_2(t)]^T
\]

\[
\begin{align*}
x_1(t) &= \lambda(t) \\
x_2(t) &= V(t)
\end{align*}
\]

Where

\[
f(X(t), t) = \begin{bmatrix}
(1 + x_1(t)) \frac{g \mu(x_1)}{x_2(t)} + \frac{r^2 M g \mu(x_1)}{x_2(t) J_\omega} \\
- g \mu(x_1)
\end{bmatrix}
\]

\[
B(X(t), t) = \begin{bmatrix}
- \frac{r}{J_\omega}, 0
\end{bmatrix}^T
\]

\[
C(t) = [1, 0]
\]
Vehicle Speed Observer

- The state space function involves vehicle speed, which is difficult measure.
- We therefore build a speed observer based on two inputs,
Actual Speed of the Vehicle

Vehicle Speed Observer
Comparison between observed and calculated
**ILC for Motor Needed Torque**

![Block diagram of ILC for Motor Needed Torque](image)

**The Learning Process**

![Graph showing the learning process](image)
**Total Learning Error**

![Graph showing total learning error over learning steps](image)

**The Learning Process**

![Graph showing adhesive coefficient, desired slip ratio, and actual slip ratio](image)
After Third Step of Learning

After Fifth Step of Learning
Case Studies

Table II
VEHICLE PARAMETERS

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>SYMBOL</th>
<th>VALUE</th>
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<tbody>
<tr>
<td>Vehicle Mass (kg)</td>
<td>$M$</td>
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<tr>
<td>Wheel Radius (m)</td>
<td>$r$</td>
<td>0.3</td>
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<tr>
<td>Rotating Inertia (kg.m$^2$)</td>
<td>$J$</td>
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<tr>
<td>Shaft Gearing ratio</td>
<td>$a$</td>
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</tr>
<tr>
<td>Maximum Motor torque (Nm)</td>
<td>$T_m$</td>
<td>300</td>
</tr>
</tbody>
</table>
Braking on a Dry Road Surface

![Graphs showing braking performance on a dry road surface.](image1)

Braking on a Wet Road Surface

![Graphs showing braking performance on a wet road surface.](image2)
Braking on an Icy Road Surface

To Probe Further


• Akira Nagasaka, Mitsuhiro Nada, Hidetsugu Hamada, Shu Hiramatsu and Yoshiaki, Kikuchi, Toyota Motor Corporation

• Hidetoshi Kato, Denso Corporation, “Development of the Hybrid/Battery ECU for the Toyota Hybrid System,” SAE Paper 981122

Thank You!