DEVELOPMENT OF ESTIMATION ALGORITHMS FOR VEHICLE’S 
MASS AND ROAD GRADE

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ABSTRACT−In controlling the longitudinal motion of electrified vehicles such as hybrid vehicles and PHEV (Plug-in Hybrid Electric Vehicles), the variation of the driving resistance loads (or driving loads) such as road grade and actual vehicle mass, is the most influential factor which limits the control performance. Measuring the driving load is not impossible, but it is costly since additional sensors have to be mounted on the vehicle. In this study, methods for estimating vehicle mass and road grade are designed to compensate for the driving loads. The proposed methods are verified using simulation tools and then evaluated experimentally.

KEY WORDS : Mass estimation, Road grade, RLS(Recursive Least Square), Longitudinal/lateral dynamics

1. INTRODUCTION

The electrified vehicles such as hybrid vehicles and PHEV (Plug-in Hybrid Electric Vehicles) require appropriate power distribution and split components. These components are very effective to transfer two power sources to the drive axle, but are vulnerable to the driving resistance load such as road grade change. Therefore, a control algorithm which can reduce or suppress jerk is essential. Estimation algorithm for the driving resistance can provide useful information to the control algorithm. The driving load of a vehicle in motion is defined as the sum of the rolling resistance, aerodynamic drags, and road grade resistance (Ohnishi et al., 2000), in which the road grade resistance is known to be the most dominant one (Wong, 1993). Measuring the driving load is not impossible, but it is costly since additional sensors have to be mounted on the vehicle. Therefore, many researches have been carried out to estimate the driving load. Kim et al. (2000, 2006) estimated turbine torque using neural network, and designed an observer to estimate vehicle driving load. Sun et al. (2008) defined the driving load as a major factor which decreases vehicle velocity and needs to be compensated. A load torque observer is designed to estimate the driving load. Cao et al. (2006) defined the parameter uncertainty and disturbance as driving load and designed an unknown input observer. Ohnishi et al. (2000) designed sensor-based and engine torque-based estimation methods to estimate road grade.

In this study, estimation methods for vehicle mass and road grade are designed to compensate for driving loads. Vehicle mass is estimated first based on existing sensors and the monitoring algorithm is designed using longitudinal and lateral dynamics models. The road grade is estimated using sensor-based and torque based approaches, respectively. The sensor-based approach utilizes longitudinal acceleration sensors mounted in a vehicle, and the torque-based method utilizes the torque information obtained from the CAN network and the estimated mass. The proposed methods are verified using simulation tools and then evaluated experimentally in field tests.

2. VEHICLE MASS ESTIMATION METHOD

For the seamless longitudinal control of the electrified vehicles, the vehicle mass needs to be monitored in real-time. Based on the longitudinal and lateral dynamics model, two algorithms are designed to estimate the mass, respectively. For the IC (Internal Combustion) engine vehicles, the mass estimation method has been developed by the authors (Han et al., 2009).

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2.1. Estimation Algorithm Based on the Vehicle’s Longitudinal Motion

The vehicle mass estimation algorithm based on the vehicle’s longitudinal motion is developed on the condition that the vehicle accelerates with little steering. The longitudinal motion of a vehicle is described as follows:

\[ \dot{y} + F_y = F_{acc} - F_{rolling} - F_{grade} \]  

where \( m \) : Mass of the vehicle  
\( \alpha_c \) : Longitudinal acceleration  
\( F_y \) : Longitudinal force acting on the vehicle  
\( F_{acc} \) : Aerodynamic drag force  
\( F_{rolling} \) : Rolling resistance  
\( F_{grade} \) : Road grade effect  

In the above equation, \( F_y \), \( F_{acc} \), \( F_{rolling} \), and \( F_{grade} \) can be calculated from the following expressions.

\[ F_y = \frac{T_{Thd\ input} \cdot N_{transmission} \cdot N_{differential} \cdot f_{efficiency}}{r_{Tire}} \]  

(2)

\[ F_{acc} = \frac{1}{2} \rho AC_d v_i^2 \]  

(3)

\[ F_{rolling} = \mu_{rolling} \cdot mg \cdot \cos \theta_{road} \]  

(4)

\[ F_{grade} = mg \cdot \sin \theta_{road} \]  

(5)

where

\( T_{Thd\ input} \) : Torque input to the transmission  
\( N_{transmission} \) : Gear ratio of the transmission  
\( N_{differential} \) : Final drive ratio  
\( f_{efficiency} \) : Efficiency of the transmission  
\( r_{Tire} \) : Effective tire radius  
\( \rho \) : Air density  
\( A \) : Frontal area of the vehicle  
\( C_d \) : Drag coefficient  
\( v_i \) : Velocity of the vehicle  
\( \mu_{rolling} \) : Rolling resistance coefficient  
\( g \) : Gravitational acceleration  
\( \theta_{road} \) : Road grade

Substituting equations (2), (3), (4), and (5) into (1), the longitudinal motion of the vehicle can be expressed as the following regression form:

\[ y(t) = \phi(t) \delta(t) \]

\[ \begin{bmatrix} y \\ \dot{y} \end{bmatrix} = \begin{bmatrix} \alpha_c - g \cdot \sin(\delta_{road}) & v_i^2 + g \\ m \end{bmatrix} \begin{bmatrix} \theta \end{bmatrix} \]  

(6)

The parameter vector, \( \theta \), includes the vehicle mass and can be estimated using the measurement vector and output \( y \). The longitudinal force, \( F_y \), is obtained from the power distribution system where the transmitted torque is calculated based on the engine torque, motor torque, and clutch engagement states. The longitudinal velocity \( v \), in a low-slip range can be approximated using the speed of the free-rolling wheels. In case of the front-wheel drive vehicle, the measured rear wheel speed from the CAN network can be used.

\[ v = \frac{(\omega_{fr} + \omega_{mr}) \cdot r_{mr}}{2} \]  

(7)

The recursive least square (RLS) algorithm (Astrom and Wittenmark, 1993) is applied to equation (6) in order to estimate the parameter vector \( \theta \), according to the following equations

\[ \dot{\theta}(t) = \dot{\theta}(t-1) + P(t) \phi(t) [y(t) - \hat{y}(t-1)] \]

\[ P(t) = P(t-1) - P(t-1) \phi(t) [1 + \phi(t) P(t-1) \phi(t)]^{-1} \phi(t) P(t-1) \]

where \( \dot{\theta}(t) \), \( \phi(t) \) and \( P(t) \) denote the estimated parameter vector, measurement vector and covariance matrix respectively.

The initial covariance matrix is chosen based on the following equation.

\[ P(0) = \alpha I \]

The size of \( \alpha \) is chosen based on uncertainty of parameters. If \( \theta(0) \) is unknown, large \( \alpha \) is used. If nominal value of \( \dot{\theta}(0) \) is known, then small \( \alpha \) is chosen.

The forgetting factor is always chosen slightly less than 1. Typical choices of \( \lambda \) are in the range between 0.98 and 0.995.

2.2. Estimation Algorithm Based on the Vehicle’s Lateral Motion

The mass estimation algorithm is designed based on the vehicle’s lateral motion. When a vehicle turns with a constant longitudinal speed, the 2-DOF bicycle model shown in Figure 2 can approximately describe the lateral motion up to a certain limit (e.g., \( \alpha \leq 0.3g \)).

\[ m \alpha_c = F_{yf} \cos \delta + F_{yr} \]

(8)

In this model, the aerodynamic drag and inclination effects are ignored. Then the vehicle mass can be estimated by applying the RLS (Astrom and Wittenmark, 1993) to the following equation.

\[ F_{yf} \cos \delta + F_{yr} = ma_c \]

(9)

Figure 2. Lateral vehicle dynamics.