

Synthesis of a Hybrid-Observer-Based Active Controller for Compensating Powertrain Backlash Nonlinearity of an Electric Vehicle during Regenerative Braking

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ABSTRACT

Regenerative braking provided by an electric powertrain is far different from conventional friction braking with respect to the system dynamics. During regenerative decelerations, the nonlinear powertrain backlash would excite driveline oscillations, deteriorating vehicle drivability and blended brake performance. Therefore, backlash compensation is worthwhile researching for an advanced powertrain control of electrified vehicles during regenerative deceleration.

In this study, a nonlinear powertrain of an electric passenger car equipped with a central motor is modeled using hybrid system approach. The effect of powertrain backlash gap on vehicle drivability during regenerative deceleration is analyzed. To further improve an electric vehicle's drivability and blended braking performance, an active control algorithm with a hierarchical architecture is studied for powertrain backlash compensation. Since the backlash in driveline is unable to be measured by a sensor, a high-level hybrid observer for backlash identification is designed at first. Then, based on the observation of the backlash traverse, a low-level switching-based active controller for powertrain backlash compensation is synthesized.

The proposed control algorithm is simulated and compared with a non-active baseline strategy under regeneration deceleration. The simulation results show that the nonlinear powertrain backlash is well compensated by the developed active control algorithm, and the vehicle drivability and blended braking performance are also significantly enhanced.

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INTRODUCTION

In urban driving situations, about one third to one half of the energy of the power plant is consumed during deceleration processes [1, 2]. As one of the key technologies of electric vehicle, a regenerative braking system, which has the ability to convert kinetic energy into electrical energy during decelerations, can effectively improve the energy efficiency of vehicle. Therefore, it has become a hot topic of research and development [3, 4, 5].

With respect to the system dynamics, regenerative braking provided by an electric powertrain is far different from conventional friction braking. Its introduction not only provides great potential for improving vehicle energy efficiency but also poses tremendous challenges to existing brake theories and control methods. Hence, it is of great importance to take the dynamic behaviour of the powertrain system into consideration in developing an advanced regenerative braking control strategy for electric vehicles.

Backlash, which introduces a hard nonlinearity into the powertrain control loop for torque generation and transmission, greatly affects the dynamic performance of a vehicle. The main source of backlash

is play between gears in the final drive and the gearbox, but other plays throughout the drivetrain add to the backlash [6]. In an electric vehicle, when the driver quickly depresses and releases the accelerator pedal or vice versa, requesting a transition from acceleration to regenerative braking or vice versa, driveline backlash is first traversed, exciting the nonlinearity, and no torque is transmitted through the shaft during this period. After contact is achieved, the impact (referred to as shunt) leads to a large half-shaft torque, which, combined with the flexibility of the powertrain, causes the unexpected driveline oscillation (referred to as shuffle) [7].

The powertrain backlash oscillation problem and its solutions have been widely investigated for conventional vehicles. In [8], an engine torque profile shaping strategy was proposed to reduce drivetrain vibration for passenger cars. In [9], an anti-jerk controller of passenger cars was designed using H-infinity algorithm. However, for an electric vehicle, especially in the regenerative deceleration situations, the driveline oscillation problem becomes much tougher. The response of an electric motor is much faster than that of an internal combustion engine, and the motor's regenerative braking torque is usually far larger than that of engine braking in a conventional car, which results in more severe oscillations. Moreover,

during a process of blended regenerative and friction braking, the application of friction braking adds a disturbance to the load side, further affecting the backlash and increasing the complexity of oscillation compensation control. Therefore, powertrain backlash compensation is important for improving vehicle drivability and powertrain control performance during regenerative deceleration, and it is worthwhile researching. In [10], a shaking vibration control was developed for pure electric car Nissan Leaf. In [11], a feedback control system was implemented to compensate for the effect of the half-shaft dynamics. However, in the above studies, although the driveline oscillation caused by shaft flexibility was considered, the nonlinear backlash was neglected in favour of a linear model. Nevertheless, the backlash do exist in the real powertrain, and its effect on drivability of electric vehicles during regenerative braking have rarely been reported.

In this study, a nonlinear powertrain of an electric passenger car equipped with a central motor is modeled using hybrid system approach, i.e. the hybrid automaton. Effect of powertrain backlash gap on vehicle drivability during regenerative deceleration is analyzed. To further improve an electric vehicle's drivability and blended braking performance, an active control algorithm with a hierarchical architecture is studied for powertrain backlash compensation. Since the backlash in driveline is unable to be measured, i.e. the contact and backlash modes of a powertrain cannot be directly obtained by a sensor, a high-level hybrid observer for backlash identification is designed at first. Then, based on the observed backlash motion, a low-level switching-based active controller for powertrain backlash compensation is synthesized. The proposed control algorithm is simulated in the regenerative braking process and compared with two baseline situations. Simulation results show that the proposed active control can compensate the powertrain backlash well, improving the control performance of the half-shaft torque and vehicle drivability significantly.

HYBRID SYSTEM MODELING FOR NONLINEAR ELECTRIC POWERTRAIN

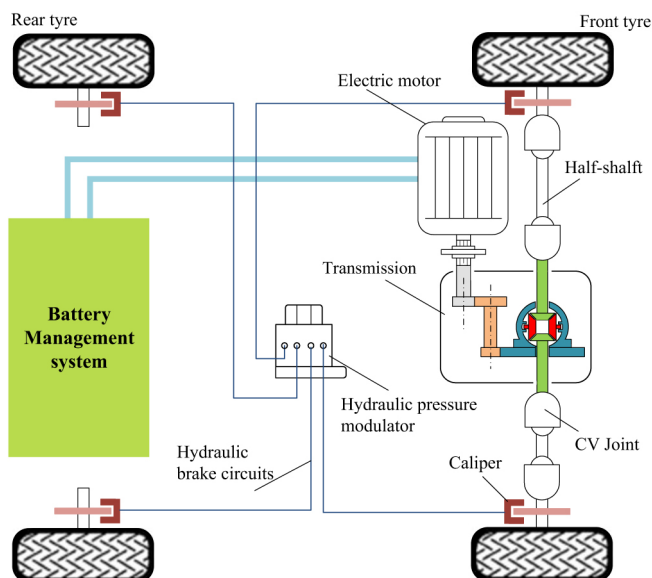


Figure 1. Overall structure of the blended braking system.

Figure 1 shows the overall structure of the regenerative and hydraulic blended braking system considered in this study. A central electric motor is installed at the front axle of the vehicle. During deceleration, regenerative braking torque transmitted by the driveline is exerted on the axle. In the meantime, friction braking torque is generated by the hydraulic modulator. The blended braking torque meets the overall braking demand. The electric powertrain, which comprises an electric motor, gearbox, final drive, differential, and half shafts, is modelled as described below.

Figure 2 shows a simplified two-inertia model of the electric powertrain used in this study. One inertia indicates the electric motor, and the other one represents the contribution of the wheel. The gearbox, consisting of the transmission, final drive, differential, and inner and outer constant-velocity (CV) joints, is located close to the motor inertia. The most important nonlinearity, which affects the driveline behaviour, is the backlash. The backlash contributions throughout the powertrain are lumped together into one single backlash angle, noted as 2α . The half shaft is modelled as a flexible one, representing its stiffness and damping properties. And the motor output torque is assumed to be equally distributed to the left and right half shafts.

Considering the effect of the electrical system dynamics, the motor torque is modelled as a first-order reaction [2], as shown in [equation \(1\)](#).

$$\tau_m \dot{T}_m(t) + T_m(t) = T_{m,ref}(t) \quad (1)$$

where $T_m(t)$ is the real value of motor torque and $T_{m,ref}(t)$ is the reference value.

The dynamic equation for the transmitted torque from the motor output shaft to the half shafts is as follows:

$$J_m \ddot{\theta}_m(t) + b_m \dot{\theta}_m(t) = T_m(t) - 2T_{hs}(t) / i_0 i_g \quad (2)$$

where J_m is the motor inertia, b_m is the viscous friction of the motor, $i_0 i_g$ is the transmission ratio, and $T_{hs}(t)$ is the half-shaft torque.

A flexible half shaft with nonlinear backlash connects the gearbox and the wheel inertia. The nonlinear model for the half-shaft torque can be given by [7]:

$$T_{hs}(t) = k_{hs} \theta_s(t) + c_{hs} \dot{\theta}_s(t) \quad (3)$$

$$\theta_s(t) = \theta_d(t) - \theta_b(t) \quad (4)$$

$$\theta_d(t) = \theta_1(t) - \theta_3(t), \quad \theta_b(t) = \theta_2(t) - \theta_3(t) \quad (5)$$

where k_{hs} and c_{hs} are the stiffness and damping coefficients of the half shaft, respectively; $\theta_d(t)$ is the shaft twist angle; $\theta_b(t)$ is the backlash position; and $\theta_1(t)$, $\theta_2(t)$, and $\theta_3(t)$ are the angles at the indicated positions on the shaft, as shown in Figure 2,

where $\theta_1(t) = \theta_m(t)/i_0 i_g$ and $\theta_3(t) = \theta_w(t)$.

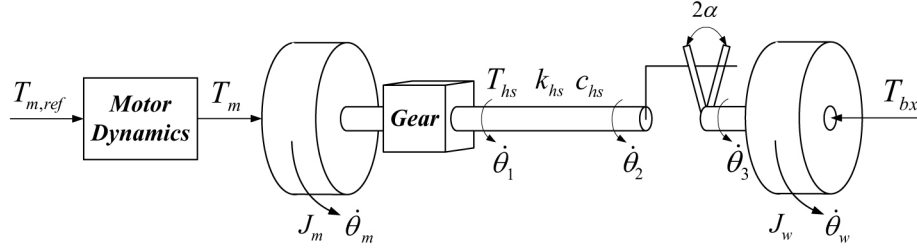


Figure 2. Two-inertia simplified model of electric powertrain system.

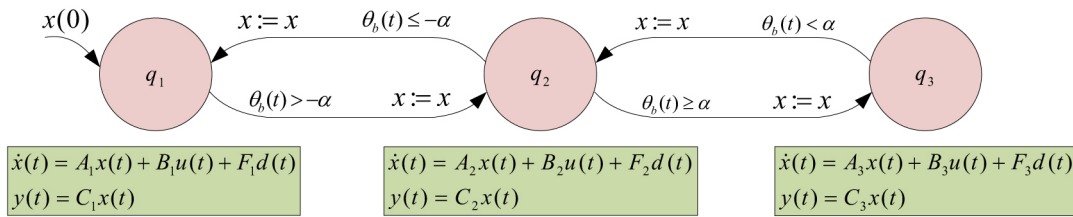


Figure 3. Hybrid automaton of electric powertrain system.

The nonlinear model for the backlash position is described by [6]:

$$\dot{\theta}_b(t) = \begin{cases} \max\left(0, \dot{\theta}_d(t) + \frac{k_{hs}}{c_{hs}}(\theta_d(t) - \theta_b(t))\right), & \theta_b(t) = -\alpha \\ \dot{\theta}_d(t) + \frac{k_{hs}}{c_{hs}}(\theta_d(t) - \theta_b(t)), & |\theta_b(t)| < \alpha \\ \min\left(0, \dot{\theta}_d(t) + \frac{k_{hs}}{c_{hs}}(\theta_d(t) - \theta_b(t))\right), & \theta_b(t) = \alpha \end{cases} \quad (6)$$

where 2α is the backlash gap size.

The dynamic equation for a driven wheel is as follows:

$$J_w \ddot{\theta}_w(t) + b_w \dot{\theta}_w(t) = T_{hs}(t) - T_{hb}(t) - T_{bx}(t) \quad (7)$$

where J_w is the wheel inertia and the road load is divided into a friction part b_w and the tyre longitudinal force T_{bx} . The friction braking torque T_{hb} , generated by mechanical hydraulic brake devices, can be considered as a disturbance to the wheel.

Due to the piecewise affine dynamics of the backlash shown in equation (6), the system presents nonlinear characteristics. It is suitable to describe the powertrain dynamics using hybrid system approach, which is a powerful system modelling methodology.

Definition A hybrid system $\mathcal{H}$ is a collection:

$$\mathcal{H} = (Q, \sigma, \psi, X, U, D, Y, \text{Init}, f, h, R)$$

where

- Q is the finite set of discrete states;
- $X \subseteq \mathbb{R}^n$, $U \subseteq \mathbb{R}^p$, $D \subseteq \mathbb{R}^n$, and $Y \subseteq \mathbb{R}^p$ are the domains of continuous state, input, disturbance, and output variables, respectively;
- $\text{Init} \subseteq Q \times X$ is the set of initial states;
- $f: Q \times X \times U \times D \rightarrow TX$ and $h: Q \times X \rightarrow Y$ are the vector fields defining the dynamics of the continuous state and output variables, and TX is the tangent space to X ;
- $R: Q \times Q \times X \rightarrow X$ describes the continuous state resets.

For an electric powertrain, if we define the contact as being positive when a half shaft is transmitting a driving torque, then the contact under regenerative deceleration is negative.

Based on the above definition of hybrid system, according to equations (1), (2), (3), (4), (5), (6), (7), the electric powertrain can be represented as:

- $Q = \{q_1, q_2, q_3\}$;
- $X = \{T_m, \theta_s, \dot{\theta}_m, \dot{\theta}_w, \theta_b\}$;
- $U = \{T_{m,ref}\}$;
- $D = \{T_{hb}, T_{bx}, T_l\}$;
- $Y = \{T_m, \dot{\theta}_m, \dot{\theta}_w\}$.