Applied Energy Symposium 2020: Low carbon cities and urban energy systems
October 10-17, 2020
Paper ID: xxxx

Optimal Power Management Strategy for Parallel HEVs in Acceleration Mode

Bo Zhang[1], Tielong Shen[2]
1. Department of Engineering and Applied Sciences, Sophia University, Tokyo 102-8554, Japan
E-mail: zhangbo@eagle.sophia.ac.jp
2. Department of Engineering and Applied Sciences, Sophia University, Tokyo 102-8554, Japan E-mail: tetu-sin@sophia.ac.jp

ABSTRACT

This paper presents a strategy for optimizing the comfortability of hybrid electric powertrains in acceleration mode. A parallel hybrid electrical vehicle (HEV) powertrain system with two motors and single turbo-charged engine is considered, and during the acceleration mode, it is assumed that the desired acceleration rate cannot be satisfied by the electrical motor only. Then, the first challenging issue is how to manage the combustion engine to assist the power generation and the power split such that the system satisfies comfortability, and the second challenging is difficulty in modeling the comfortability, e.g. analytically describing the human feeling. This paper exploits a black-box module to evaluate the comfortability quantitatively which is used in automotive industry. A genetic algorithm (GA) is applied to seek the optimum power split and gear schedule in acceleration mode which improves the comfortability evaluated by the module. Finally, the simulation results conducted on a simulator with practical background are demonstrated where to validate the proposed design approach.

Keywords: ride comfort, black-box module, hybrid electric vehicles (HEVs), genetic algorithm (GA)

1. INTRODUCTION

A wide variety of optimization algorithms for hybrid electrical vehicle (HEV) control have been published. However, most of the existing work pay attention to the optimization strategy and fuel efficiency without the human sensory evaluation considered. Studies indicated that the uncomfortable driving may cause traffic accidents and lead to negative effects for driver/passengers [1]. For the traditional automobile with single energy source, vehicle ride comfort is usually evaluated by the stability performance [2]. Moreover, because of the discontinue dynamics and different architectures of hybrid powertrain system in mode transitions, it usually results in severe jerk of vehicle and unpleasant ride feeling. In addition, it has been suggested that both jerk and acceleration contributed significantly to the performance of ride comfort [3]. In general, an electric motor is unable to provide enough energy to generate a desired acceleration rate during acceleration process. The management of the combustion engine such as the intervention time and the power distribution contribute to the rate of acceleration, which leads to different driving feeling.

In summary, the energy management between motors and engine and gear shifting are inevitable during acceleration process for hybrid powertrain system because of the characteristics of system. The noticeable jerk or torque fluctuation caused by the operations may lead to an uncomfortable driving sensation. Therefore, a reasonable arrangement of the power between the energy sources has great potential for better system comfortability. The aim of this work is to deal with these issues such that improve ride comfortability and hold smooth transition operation during a desired acceleration process. The main contributions are as follows: A parallel HEV powertrain model with two motors and single turbocharged engine is built firstly. Then a module for comfortability evaluation is presented to quantitatively describe the performance of ride comfortability. It is a black-box module designed by the experts from Toyota, which is exploited to evaluate the

---

Selection and peer-review under responsibility of the scientific committee of CUE2020

comfortability quantitatively. Because the evaluation function is an implicit function with respect to acceleration and jerk, the genetic algorithm (GA) technique is employed to seek the optimal power split and gear schedule satisfying the desired constraints in an acceleration mode to improve the ride comfortability.

2. HYBRID POWERTRAIN MODEL

The architecture of the considered parallel HEV power- train is shown in Fig.1. The powertrain comprises two motors and a turbo-charged engine. MG1 and MG2 are two electrical motors with different motor characteristics. In Fig.1, τ_e, τ_{m1}, and τ_{m2}, denote the torques of the engine, MG1 and MG2, respectively, ω_e, ω_{m1} and ω_{m2} represent the speeds of the engine,MG1 and MG2, respectively, τ_c and τ_t denote the input and output torques of the gear box, τ_d and τ_w define the input and output torques of the differential gear, ω_d and ω_w are the relevant rotation speed, and v is the longitudinal speed of the HEV.

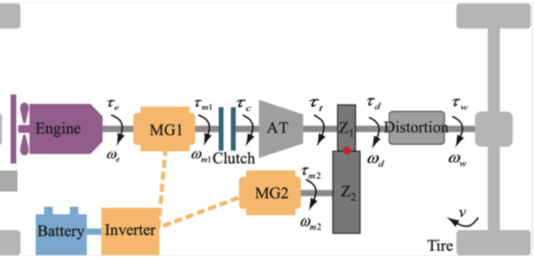


Fig. 1: The structure of the powertrain system.

We denote that 0 means clutch is off and 1 means clutch is on. The dynamics of the powertrain system shown in Fig.1 are derived as the following equations with the status of the clutch.

$(a).\ CL = 0$

$$\begin{cases} \left[I_{\Sigma d_2}\eta_f G_f^2 + \left(I_{\Sigma\omega} + R_{tire}^2 M\right)\right]\dot{v} = \dfrac{\eta_f G_f G_m \tau_{m2}}{R_{tire}} - F(v) \\ (I_e + I_{m1})\dot{\omega}_e = \tau_{m1} + \tau_e \\ \omega_{m2} = G_f G_m \dfrac{v}{R_{tire}} \end{cases}$$

$(b).\ CL = 1$

$$\begin{cases} \left[\left(I_{\Sigma d_1} + I_{\Sigma d_2}\right) + \left(I_{\Sigma\omega} + R_{tire}^2 M\right)\right]\dot{v} = \\ \dfrac{\eta_f G_f\left[\eta_t i_g(\tau_{m1} + \tau_e) + G_m\tau_{m2}\right]}{R_{tire}} - F(v) \\ \omega_e/\omega_{m1} = G_f i_g \dfrac{v}{R_{tire}} \\ \omega_{m2} = G_f G_m \dfrac{v}{R_{tire}} \end{cases}$$

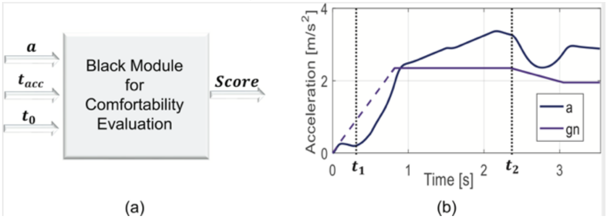
where I denotes the rotational inertia of the relevant mechanical structure, $I_{\Sigma d_1}, I_{\Sigma d_2}$ and $I_{\Sigma\omega}$ denote the accumulated inertia functions of the components, M, R_{tire} and η_f represent the vehicle mass, the wheel radius of the tire, and the transmission efficiency, respectively, i_g and η_t denote the gear ratio and efficiency of the gear box, and $F(v)$ is the road load that can be written as

$$F(v) = \mu_r \mathrm{Mgcos\theta} + \frac{1}{2}\rho A C_d v^2 + Mgsin\theta$$

where $\rho, A,$ and C_d denote the air density, the frontal area of the vehicle and the air drag coefficient, respectively, μ_r and g are coefficient of rolling resistance and gravitational acceleration, and θ is the road slope.

3. OPTIMAL CONTROL PROBLEM

To evaluate the ride comfortability, a human feeling function is presented by experts and engineers from Toyota. It is a complicated function with respect to the acceleration time, acceleration and jerk, and is unable to be expressed explicitly. The black module for comfortability evaluation is shown as Fig.2 (a). To explain clearly, the different acceleration curves with different scores are sketched in Fig.2 (b).



(a)

(b)

Fig. 2: The visual examples of human feeling function. (a) The structure and application of the function block. (b) The acceleration curve with score = 60.5141.

The proposed acceleration process is shown as Fig.3, where the blue line denotes as the acceleration, the purple line represents the gear schedule, and the orange line is the velocity curve. The proposed HEV drives at a constant speed v_0 under EV mode that motor2 provides the energy, individually. The acceleration process is from t_0 to t_f that can be described as follows. At the initial time t_0, the vehicle begins to speed up to a specified terminal velocity v_f under HEV mode. t_1 and t_2 are denoted as the first and second shifting time. During the acceleration process, the motors and engine work together to propel the vehicle. Although the engine is on from the initial time t , it is allowed to provide energy until the speed of engine reaches a reasonable value at time t_1 An initial gear number gn1 is chosen at time t_1, it means that the clutch is on at this point. Then, the vehicle drives until time point t_2, anther gear number gn_2 is decided to obtain a comfortable acceleration. The vehicle speeds up to the terminal velocity v_f at the terminal time t_f, where t_f is satisfied by a specified value. Moreover, the whole acceleration time is denoted as t and the initial gear schedule gn_1 is given to reduce mechanical friction in acceleration mode. Thus, the power split ρ between the two motors, the second shifting time t_2 and gear schedule gn_2 that should be optimized during the acceleration process influence the acceleration curve, which is shown as the lines in the upper figure of Fig.3.

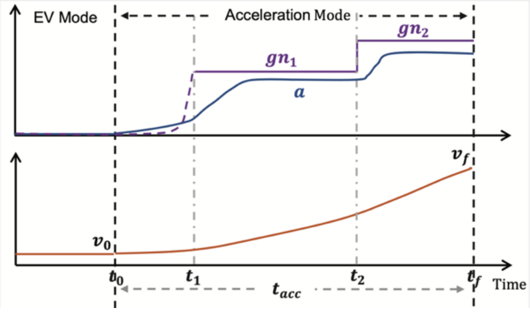


Fig. 3: The comfortability problem in acceleration mode.

In this work, we aim to determine the optimal second shifting time, gear schedule and power split between the two motors in acceleration mode such that improve ride comfortability. The throttle of the engine is required to be full open after ignition. A gear shifting is necessary after the engine starting working for improving the engine efficiency during the acceleration process. In this paper, a GA-type control scheme is proposed to maximize the index of the comfortability evaluation function. To sum up, the optimization problem is formulated:

$$\max_{u} J(a)$$

$$\text{s.t.}\begin{cases} [\dot{v}, \dot{\omega}_e]^T = f[\tau_{m1}, \tau_e, \tau_{m2}, gn_2, t_2] \\ a = \dot{v} \\ v(t_0) = v_0, \ \ v(t_f) = v_f \\ P_{m1} = \rho P_{battery} \\ P_{m1} = \dfrac{P_{battery} - P_{m1}}{\omega_{m2}} \\ \tau_{m1,min} \leq \tau_{m1} \leq \tau_{m1,max} \\ \tau_{m2,min} \leq \tau_{m2} \leq \tau_{m2,max} \\ \tau_e = \tau_{e,max} \\ \omega_{e,min} \leq \omega_e \leq \omega_{e,max} \\ t_f \leq t_{max}, \quad 0 \leq \rho \leq 1 \\ t_1 + 0.7 \leq t_2, \ \ t_2 + 0.7 \leq t_f \end{cases}$$

where J denotes as the unknown human feeling function, $J: A \rightarrow R$ is a functional on a function space A, $x = [v, \omega_e]^T$ denotes the state variables and the inputs $u = [\rho, t, gn]^T$ represents the power split ratio between the two motors, the second shifting time, and the second gear number. A linear delay within $0.7\,[s]$ of shifting is inevitable for the proposed parallel powertrain structure in this paper. Therefore, the time interval between the two shifting should be over $0.7\,[s]$.

Moreover, τ_e is predefined to be the maximum torque as the throttle of the engine is supposed to be full open in accelera- tion mode, it means that $\tau_e = \tau_{e,max}$.

4. RESULTS

The first shifting time t_1 is defined as the time when clutch is on, and an initial gear $gn_1 = 3$ is given. During the acceleration process, another shifting is required, and the vehicle should reach the desired terminal velocity before the time t_f . The optimal result of the powertrain control for the index value $J = 76.8045$ can be observed in Fig. 4 and Fig. 5, where the terminal time is t_f= 3.61 [s], the second shifting time is $t_2 = 2.34\,[s]$ and gear number is $gn_2 = 4$.

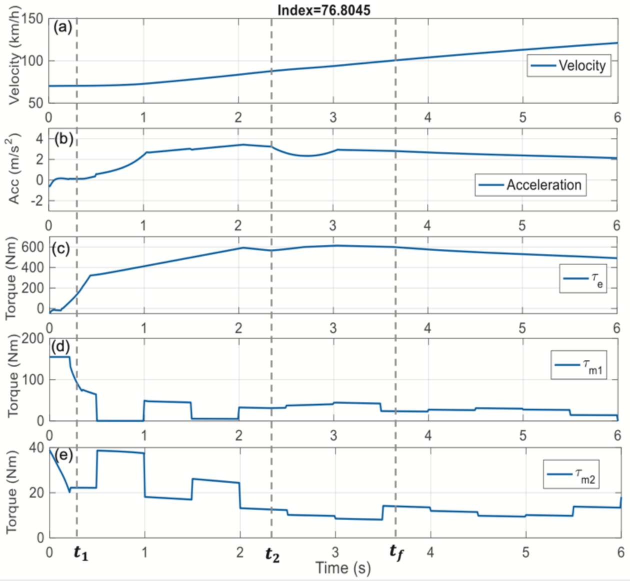


Fig. 4: The simulation results of hybrid powertrain. From top to bottom, the figures show the curves including (a) the velocity, (b) the acceleration, (c) the engine torque, (d) the Motor 1 torque, and (e) the Motor 2 torque, respectively.

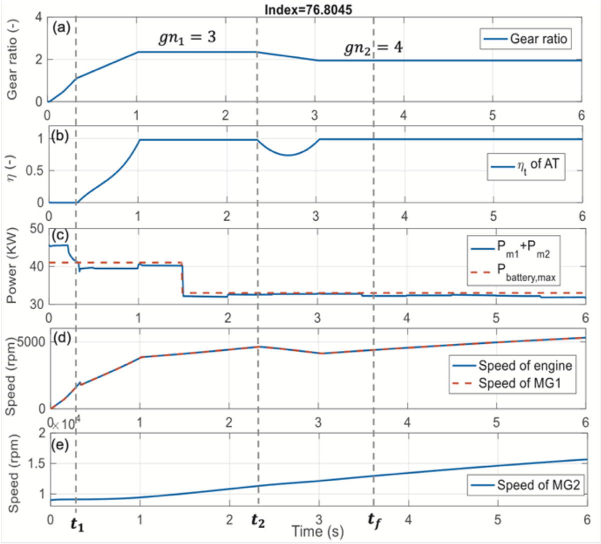


Fig. 5: The simulation results of hybrid powertrain. From top to bottom, the figures show the curves including (a) the gear

ratio, (b) the efficiency of gear box, (c) the power of MG1 and MG2, (d) the speed of MG1 and engine, and (e) the speed of MG2, respectively.

5. CONCLUSTON

In this paper, a GA-based comfortability control for hybrid powertrain system is presented. The considered HEV transmission system includes two electric motors, single turbo-charged engine and a clutch that jointly decide the operating mode (EV or HEV). Two dynamic models characterize the behaviors of the powertrain under different operating modes. We assume that the motors are not capable enough to generate the power with a desired acceleration rate. The combination of mode shift, power split and gear schedule results in the fluctuation of velocity and acceleration, which leads to obvious driving feeling. Thus, an optimal comfort- ability controller is designed to avoid unreasonable jerk and acceleration and improve the performance of ride comfort in acceleration mode. To evaluate the performance of ride comfort, a black-box module to evaluate the comfortability quantitatively is presented by the experts from Toyota. Then, the GA technique is proposed to seek the optimal power split and gear schedule for an unknown performance function to improve the ride comfortability. To observe the effective- ness of the proposed strategy, simulation is evaluated under a predefined acceleration scenario. The results show that the proposed strategy can improve ride comfortability and hold smooth transition operation in a specific acceleration mode.

REFERENCE

[1] A K. Nandi, D. Chakraborty, and A. Vaz W, Design of a comfortable optimal driving strategy for electric vehicles using multi-objective optimization, Journal of Power Sources, 283: 1–18, 2015.

[2] A E. Geweda, M A. El-Gohary, et al., Improvement of vehicle ride comfort using genetic algorithm optimization and PI controller, Alexandria Engineering Journal, 56: 405-414, 2017.

[3] P R. Grant, B. El-Haycock, Effect of jerk and acceleration on the perception of motion strength, Journal of Aircraft, 45: 1190-1197, 2008.