Optimization on energy management strategy with vibration control for hybrid vehicles

Yifan Wei, Yuning Wang and Zhichao Hou

October 16, 2019

Optimization on energy management strategy with vibration control for hybrid vehicles

Yifan. Wei 1[0000-0001-6500-7658], Yuning. Wang 1#[0000-0003-2087-2503] and Zhichao. Hou 3*

School of Vehicle and Mobility, Tsinghua University, Haidian district, Beijing, China
#: Yuning. Wang: the co-first author. They contribute equally to the study.
`houzc@tsinghua.edu.cn`

Abstract. Hybrid electric vehicles (HEVs) are considered to be one of the mainstream for the future automotive market, and various studies have been carried out to save energy. However, most of the current driving management strategies only take energy economy into consideration, without any optimization for vibration control. As a result, the shock and dizziness are usually more severe with an HEV than gasoline vehicles. Hence, this paper developed vibration control and applied it in fuel consumption optimization. A multi-objective optimal problem was defined and solved with combined vibration control and energy management. Numerical simulations demonstrate that vehicle vibration performance is greatly improved at a cost of limited extra energy consumption.

Keywords: Hybrid Vehicle, Vibration control, Energy management.

1 Introduction

Because of the potential to save energy and reduce emissions, hybrid electric vehicles (HEVs) are considered to be one of future vehicle trends. For parallel hybrid vehicles, Kim designed a fuzzy control strategy to improve engine efficiency and reduce emissions [1]. Chen proposed an online adaptive control strategy, obtaining the most energy-saving solution by dynamic programming (DP) algorithm [2].

Panday summarized mainstream energy management strategy methods [3]. However, none of them takes vibration control into consideration. As a result, the shock on HEVs are usually more severe than on gasoline vehicles. Motivated with such an observation, this study introduces a novel energy management strategy which combines vibration control and energy consumption optimization.

In the field of vehicles power system vibration analysis, a lot of researches have been conducted. Doughty used the extended transfer matrix to analyze the vibration of a damped crankshaft and solved it with an iterative method [4]. Wakabayashi achieved analysis on the torsional vibration as well as the axial and lateral vibration of an engine crankshaft using a three-dimensional model [5].

In this study, a multi-objective optimal problem was defined and solved based on Toyota Prius 4. By incorporating vibration control into energy optimization, the vehicle driving management system is amended.

2 Dynamic modelling

2.1 Mechanical model of drive line torsional vibration

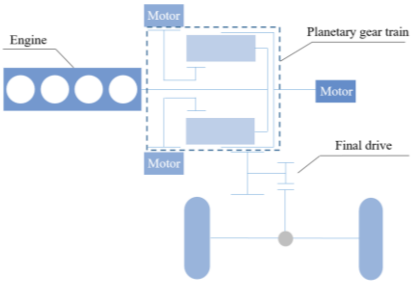


Fig. 1. Dynamic model of Toyota Prius 4

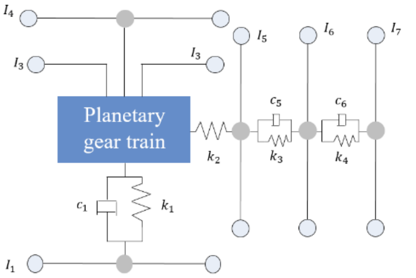


Fig. 2. Prius 4 transmission system vibration model

As shown in Fig. 1, the overall transmission system consists of the engine, planetary gear train, final drive, motor and drive shaft. The engine is directly attached to the planet carrier. One motor is connected to the sun gear, and another one to the ring gear. The final drive and the rim are also linked to the ring gear. Power is transited to the wheels through the differential from final drive. Final drive and drive shaft can be simplified to spring damping structure. The pivotal problem of vibration analysis should be focused on the planetary gear system. In this study all gear meshing is modelled and calculated by international stiffness simplification formula, where k' is the stiffness of single gears, and ε_α is gear face coincidence:

$$k_r = k'(0.75\varepsilon_\alpha + 0.25) \tag{1}$$

The overall vibration model of Prius is demonstrated as Fig. 2. Section status and properties are shown as Table 1 [6].

Table 1. Status and properties of Prius 4 vibration model

Name	Section	Result	Name	Section	Result
I_1	Crankshaft	$0.28\ \mathrm{kg \cdot m^2}$	k_1	Shock absorber	$620\ \mathrm{Nm/rad}$
J_c	Gear carrier	$0.06\ \mathrm{kg \cdot m^2}$	k_2	Gear stiffness	$401\ \mathrm{kNm/rad}$
I_3	Sun gear	$0.03\ \mathrm{kg \cdot m^2}$	k_3	Gear stiffness	$5830\ \mathrm{Nm/rad}$
J_p	Plane gear	$0.01\ \mathrm{kg \cdot m^2}$	k_4	suspension	$8600\ \mathrm{Nm/rad}$
I_4	Ring gear	$0.1\ \mathrm{kg \cdot m^2}$	c_1	Shock absorber	$4.77\ \mathrm{Nm \cdot s/rad}$
I_5	Final drive	$0.1\ \mathrm{kg \cdot m^2}$	c_5	Final drive	$47.8\ \mathrm{Nm \cdot s/rad}$
I_6	Wheels	$0.5\ \mathrm{kg \cdot m^2}$	c_6	Wheels	$286.5\ \mathrm{Nm \cdot s/rad}$
I_7	Car Body	$120\ \mathrm{kg \cdot m^2}$			

2.2 Control model of relative power devices

The model is based on commonly used energy management strategy (EMS) modelling [7]. In normal working range, it can be estimated that the temperature, open circuit voltage, and charge and discharge impedance of the battery are basically constant value. Therefore, the dynamic characteristics of SOC of the battery could be expressed as in paper [8]. Study has indicated that the engine steady-state response is completely sufficient for the estimation of fuel consumption [9]. The dynamics of motors are not a critical concern in this paper, so it can be simplified as a first-order process. Generally, the longitudinal dynamic equation and resistance can be described as in paper [7]. Toyota Hybrid System is selected in this paper, and the relationship between the components of the planetary gear can be expressed as in the paper [10].The whole vehicle model can thus be described as (2):

$$\begin{cases} I_{veh}\dot{\omega}_W = T_{veh} - T_f \\ T_f = [m_{veh} g(\sin\theta + f_r\cos\theta) + \frac{1}{2}C_D A v_{veh}^2]\cdot r_W \\ T_{veh} = \eta_T(\frac{\omega_{Eng}}{\omega_r}T_{Eng} + \frac{\omega_{MG1}}{\omega_r}T_{EM1} + \frac{\omega_{MG2}}{\omega_r}T_{EM2}) + T_{brake} \\ I_{veh} = m_{veh} r_W^2 + 4I_W + [(\frac{\omega_{Eng}}{\omega_r})^2 I_{Eng} + (\frac{\omega_{MG1}}{\omega_r})^2 I_{EM1} + (\frac{\omega_{MG2}}{\omega_r})^2 I_{EM2}] \end{cases} \tag{2}$$

where T_r is the output torque on the ring gear， ω_r is the ring gear speed， ω_{Eng}， ω_{MG1}， ω_{MG2}， T_{Eng}， T_{MG1}， T_{MG2} are output speed of the engine, motor 1st and motor 2nd , and output torque of the three devices respectively.

2.3 Energy management model

The cost function concludes three items, namely fuel consumption rate, equivalent motor power and loss of battery power when discharging and charging, as shown by (3).

$$J_{fuel} = P_{eq}(t) + \lambda P_{bat}(t) = Q_l\dot{m}_f(t) + P_{MG}(t) + \lambda(t)\dot{SOC}(t)V_{OC}\mathrm{Q} \tag{3}$$

where Q_l is the low calorific value of the fuel, $\dot{m}_f$ is the rate of fuel consumption, $P_{eq}(t)$ is the equivalent power of engine and motor, $P_{MG}(t)$ is the power of two motors, $\lambda(\mathrm{t})$ is the coefficient related to the state of battery. Apart from torque and speed range restricted by MAP figure of engine and motor, there are limitations, $T_{MG}\cdot\omega_{MG}\cdot\eta_{MG}^k \leq P_{bat}^{max}$, $20\% \leq \mathrm{SOC} \leq 80\%$, to ensure the battery working in the linear interval [11].

3 Controller Design

Comfort experienced by passengers in a car is mainly related to the vibration acceleration transferred from car body to the human body. Therefore, in the improved energy management strategy, the following vibration control index is one optimization target function besides total energy consumption.

$$J_{NVH} = \int_{t_0}^{t_f} [a_1 \ddot{\varphi}^2] \, dt \tag{4}$$

where a_1 is a constant while t_f and t_0 represent the beginning and ending time of test.

A practical and feasible method for combining energy and vibration is local optimal control: first derive a solution according to energy, then sacrifice a part of energy, relax the solution to a range, and find the condition which has the least J_{NVH}. Here, the priority of fuel consumption is higher than the priority of vibration control. The new energy management strategy can be concluded by Fig. 3. First, external conditions are given by driving demand and road conditions: demand torque T_r and speed ω_r and derive the original switch torque T_{sw0} according to traditional energy strategy. Then loose the limitation of energy consumption, set the largest energy sacrifice that could be accepted and derive the available switch range $[T_{sw0} + \Delta T, T_{sw0} - \Delta T]$. After getting test range, try every switch torque strategy by traverse algorithm, and find the solution which has the lowest J_{NVH}. Hence the new power management system is achieved.

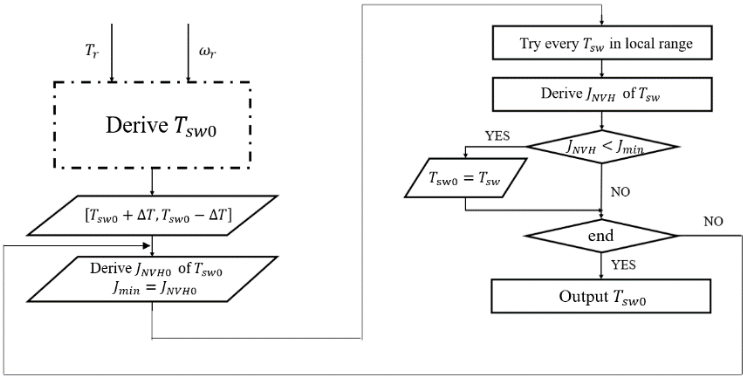


Fig. 3. New energy management strategy algorithm

4 Numerical simulations and analysis

In order to find the mode-switch boundary of global driving management system, numerical simulations were made using Simulink and Carsim. After building a model of planetary train and engine, local vibration optimization at sacrificial fuel consumption was applied to optimize the final system. A set of switch points are re-calculated according to the J_{NVH} result, as demonstrated in Tables 2-3 and Fig. 4.

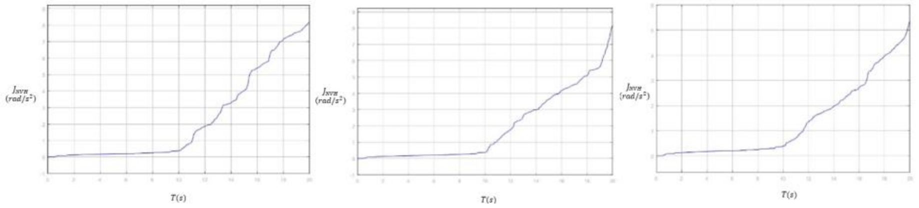
When considering the influence of vibration, the local optimal solution is when the demand torque is $62\ Nm$, while the optimal solution considering only the fuel consumption is $59\ Nm$. It is worth noting that, at $T_{sw} = 57\ Nm$, the number of vibrations has changed, which is likely to be that the system has reached resonance. Generally speaking, the switch time is slightly delayed. With sacrifice of energy consumption, the total vibration level (shown by J_{NVH}) can be reduced to 83.6% when required speed is $150\ \mathrm{rad/s}$ and 95% when required speed is $50\ \mathrm{rad/s}$.

Table 2. J_{NVH} of vehicle under different switch Torque ($\omega_r = 50\ \mathrm{rad/s}$)

$T_{sw}(Nm)$	**58**	**59**	**60**	**61**	**62**	**63**	**64**	**65**	**66**	**67**
J_{NVH}	3.1	2.8	2.6	2.6	2.7	2.7	2.7	2.9	3.1	3.4

Table 3. J_{NVH} of vehicle under different switch Torque ($\omega_r = 150\ rad/s$)

$T_{sw}(Nm)$	**55**	**56**	**57**	**58**	**59**	**55**	**56**	**57**	**58**	**59**
J_{NVH}	5.8	5.7	10.0	5.5	5.2	4.8	4.6	4.5	4.5	4.6



(a) (b) (c)

Fig. 4. (a)-(c) are the results of $\mathrm{J_{NVH}}$ under $\mathrm{\omega_r = 50rad/s}$ when $\mathrm{T_{sw} = 58, 60, 64Nm}$

The simulation results on Carsim of comparison between normal running car and the car with vibration optimization are shown in Fig. 5.

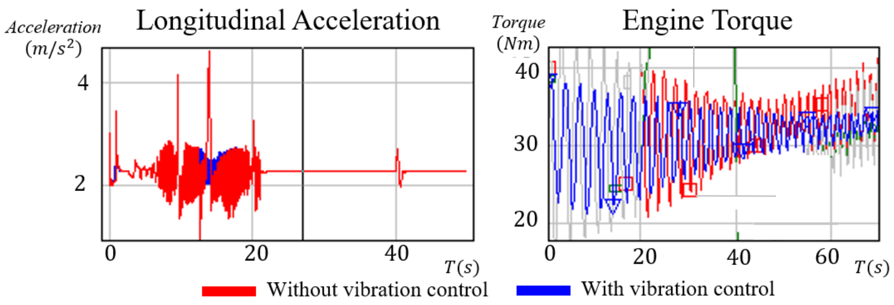


Fig. 5. (a)-(b) Carsim-Simulink results

Compared with the blue curve, the red curve in Fig. 5. (b) shows that the vehicle without vibration control is superior in fuel economy and dynamics because the output torque is relatively higher and thus it can reach the target speed faster. However, it can be seen from Fig. 5. (a) that the longitudinal acceleration of the red one is more fluctuating and the vibration level is more severe. According to the vibration target cost function described in Controller Design, the human comfort is sacrificed. This is the "trade-off" between engine energy management and vibration control. Although the red car has stronger power than the blue one, it will relatively damage the comfort of passengers. Hence, delaying this switch point would relieve vibration. This is consistent with the simulation result derived from Tables 2-3 and Figure 4.

5 Conclusions

In this paper, a novel energy management strategy is introduced, which combines vibration control and energy consumption reduction. This multi-objective optimal problem was exemplified with Toyota Prius. After combining vibration control and energy optimization, the total driving control management system is amended. According to the simulation results, the switch time with the new strategy is later than the one without vibration control, but can avoid severe vibration. Also, this result reflects a "trade-off" relationship between engine energy management and vibration control. Certain level of fuel economy is sacrificed to satisfy the passenger comfort, which is reasonable for hybrid vehicle development.

References

1. Kim, J., Kang, J., Choi, W., Park, J., Byun, S., ... & Kim, H. Control algorithm for a power split type hybrid electric vehicle. In *SPEEDAM 2010* (pp. 1575-1580). IEEE (2006).
2. Chen, Z., & Mi, C. C. An adaptive online energy management controller for power-split HEV based on dynamic programming and fuzzy logic. In *2009 IEEE Vehicle Power and Propulsion Conference* (pp. 335-339). IEEE (2009).
3. Panday, A., & Bansal, H. O. A review of optimal energy management strategies for hybrid electric vehicle. *International Journal of Vehicular Technology*, *2014* (2014).
4. Doughty, S. Transfer matrix eigensolutions for damped torsional systems. *Journal of vibration, acoustics, stress, and reliability in design*, *107*(1), 128-132 (1985).
5. Wakabayashi, K., Honda, Y., Kodama, T., Shimoyamada, K., & Iwamoto, S. The Effect of Typical Torsional Viscous-Friction Damper on the Reduction of Vibrations in the Three Dimensional Space of Diesel Engine Shaftings. *SAE Transactions*, 1852-1872 (1993).
6. Prokhorov, D. V. Toyota Prius HEV neurocontrol and diagnostics. *Neural Networks*, *21*(2-3), 458-465 (2008).
7. Li, L., Wang, X. Fuel consumption optimization for smart hybrid electric vehicle during a car-following process. *Mechanical Systems and Signal Processing*, *87*, 17-29 (2017).
8. Hu, X., Murgovski, N., Johannesson, L., & Egardt, B. Energy efficiency analysis of a series plug-in hybrid electric bus with different energy management strategies and battery sizes. *Applied Energy*, *111*, 1001-1009 (2013).
9. Sciarretta, A., Serrao, L., Dewangan, P. C., Tona, P., Bergshoeff, E. N. D., Bordons, C., ... & Hubacher, M. A control benchmark on the energy management of a plug-in hybrid electric vehicle. *Control engineering practice*, *29*, 287-298 (2014).
10. Liu, J. , Peng, H. , & Filipi, Z. . Modeling and analysis of the toyota hybrid system. Journal of Performance of Constructed Facilities, 23(6), 399-405 (2005).
11. Kim N，Cha S. Optimal control of hybrid electric vehicles based on Pontryagin''s Minimum Principlc[J]. IEEE Transactions on Vehicular Tech-nology, 19(5):1279-1287 (2011).