

Optimal Engine Starts of an Input-Split Hybrid Electric Vehicle

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ABSTRACT

Engine start-stop system is one of the main mechanisms for fuel saving in hybrid electric vehicles (HEVs). During those transient events, especially during engine starts, the engine torque pulsations can be an NVH issue if there is direct mechanical coupling between the engine and the driveline. In addition, engine starts may also result in the interruption of driving torque. The fast torque response of the electric machines provides a possible solution to mitigate the output torque fluctuation. But the effect is limited by the capability of these two electric machines due to the three missions they must satisfy simultaneously, i.e., starting the engine, compensating the torque pulsations and providing the demanded driving torque. To thoroughly understand this problem and propose possible solutions, in this study, we developed an input-split HEV powertrain model with a grounding clutch. The Dynamic Programming (DP) technique is adopted as the optimization approach to investigate the maximum output torque we can have without any torque error during engine starts. At the same time, the relationship between these two conflicting goals is achieved and the optimal solutions can be divided into four parts depending on the driver demand torque, from the minimum engine start time solution to the maximum driver torque demand solution. Based on the DP results, a control algorithm is proposed to achieve smooth and quick mode transition from the EV mode to power-split driving while meeting the driver torque demand.

CITATION: Zhuang, W., Kum, D., Peng, H., Wang, L. et al., "Optimal Engine Starts of an Input-Split Hybrid Electric Vehicle," *SAE Int. J. Alt. Power.* 4(2):2015, doi:10.4271/2015-01-1227.

INTRODUCTION

The hybrid electric vehicles (HEVs) have gained a healthy market share and are expected to grow very quickly in the next decade because of the upcoming fuel economy and carbon emission requirements [1]. The majority of HEVs available on the market are power-split HEVs. They mostly utilize planetary gears (PGs) to connect the powertrain elements (the engine, electric machine and the driveline). Engine start-stop is recognized as one of the most important features for both mild and strong hybrids to reduce fuel consumption. For power-split HEVs, there can be mode transitions from the EV mode to the power-split driving mode. This transition may cause NVH and drivability concerns. Many existing literatures focused on achieving the quick engine start and NVH reduction simultaneously. For example, Ming Kuang investigated the engine start-stop process, analyzed the root reason for the engine start-stop

NVH [2] and developed an active damping wheel-torque control system with power source coordinated control to suppress the driveline oscillations [3]. Sameh et al. presented a theory that utilized the permanently engaged starter or high power starter to reduce engine start duration and noise [4]. Another study by Canova et al. investigated the engine start problem of the diesel HEV equipped with a belted starter/alternator (BSA) and proposed a closed-loop controller to crank up the engine in minimum duration [5].

Drivability is another important vehicle performance metric. The drivability issue usually occurs during mode transitions of hybrid vehicles because the electric machine must provide the driving torque and start the engine simultaneously (unless a separate starter is used). A study by Don Colvin et al. presented the challenges related to drivability for a Modular Hybrid Transmission (MHT) system and

developed remedies [6]. Junzhi Zhang et al. optimized the clutch control and cooperation of the engine and motor to reduce the vehicle jerk, and then improve the drivability performance [7]. Another study by Dongsuk Kum et al. explored theoretical drivability limits and the optimal control strategies during engine-starts. Based on the results of dynamic programming (DP), the tradeoff between the engine start time and drivability is achieved, and a state feedback controller is developed to realize the real-time control [8]. Some researchers achieved smooth and quick mode transition through fuzzy gain-scheduling proportional-integral-derivative (PID) controller or model reference control [9, 10].

All of the engine start studies mentioned above focus on parallel HEV or power-split HEV equipped with an engine-disconnect clutch. For power-split HEV without an engine disconnect clutch, the situation is very different. For example, Prius tends to suffer the driving torque interruption or the vehicle jerk issue caused by the engine torque pulsations during engine start process due to the mechanical connection between the engine and the driveline. This kind of interruption or disturbance is always at low-frequency. That may easily lead serious NVH (noise, vibration and harshness) problem which will affect the quality of the ride and the comfort of the drivers and passengers. The quick torque response of the electric machines provides a possibility to compensate the torque disturbance. Shuji Tomura et al. developed two motor controllers to compensate the engine torque pulsations and reduce the torsional vibration [11]. However, to the best of our knowledge, the drivability of this power-split powertrain has never been investigated.

In this paper, we will focus on the optimization of vehicle drivability for Prius kind HEVs during the engine start and also searching the drivability performance limits. In addition, the relationship between the quick engine start and the driver torque demand error are also studied, when considering the effect of using the electric machine to cancel the engine torque pulsations on the engine start time

VEHICLE CONFIGURATION

The most popular HEV production vehicle, Prius, is a typical power-split configuration HEV utilizing a planetary gear (PG) to connect the engine and output driveline. It has a better fuel economy and emission performance than series and parallel HEVs because it has the common merits in both of these two. However, clutches can be added between the powertrain elements (the engine, electric machines and output driveline) and the PG to obtain more configuration choice and multiple driving modes [12]. One of the typical examples (namely Prius+) is adding a grounding clutch to connect with the carrier gear, as shown in the Fig.1. Once the clutch is grounded, the generator can provide extra power to push the vehicle forward in EV mode as shown in Fig.2 (its equivalent lever diagram). If not considering the limit of battery power, it can achieve a better launching and acceleration performance compared with the original Prius. Fig.3 shows the difference of effective torque available in the driveline between Prius and Prius+. The parameters of each component for these two configurations are the same and listed in the Table 1.

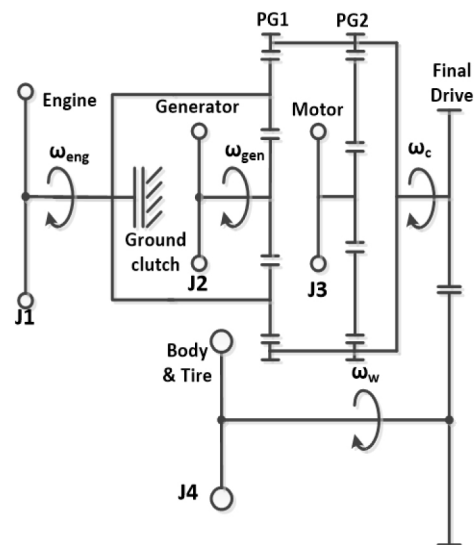


Figure 1. the kinematic diagram of the input-split HEV with a ground clutch and speed reduction gear

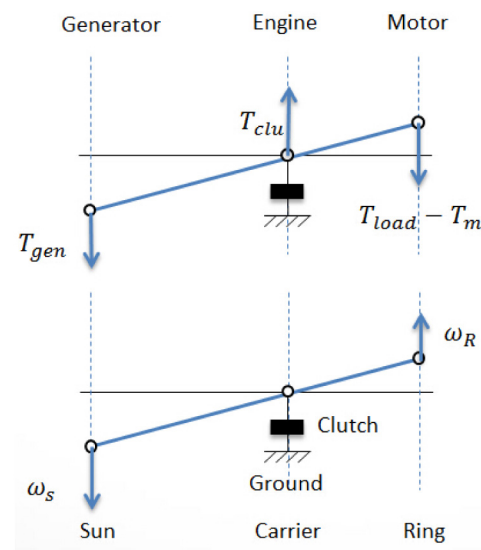


Figure 2. the lever diagram of Prius+

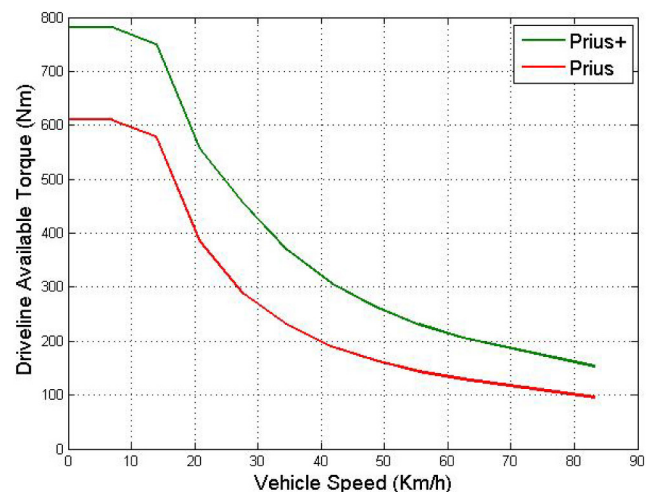


Figure 3. the torque comparison between Prius and Prius+ Documents
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Table 1. the parameters of the vehicle

Name	Parameter	value
Gasoline Engine	Displacement	1.8L, 4 cylinder
	Maximum Power	73kW @ 5200r/min
	Maximum Torque	143Nm @ 4000r/min
Motor	Maximum Power	30 kW
	Maximum Torque	300Nm
Generator	Maximum Power	15Kw
	Maximum Torque	55Nm
Planetary	Gear Ratio (R:S)	2.6:1
Final Drive	Gear Ratio	3.905
Vehicle	Mass	1200kg

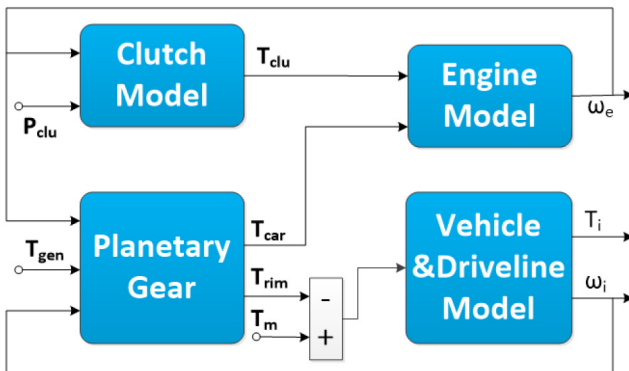


Figure 4. Block diagram of the overall powertrain model

ENGINE START MODEL DEVELOPMENT

A control-oriented model of the power-split powertrain for engine start is designed to understand the system dynamics and to assess the drivability performance in this section. Figure 4 shows the block diagram of this model. Basically, the model is composed by four main subsystems, the clutch model, engine dynamics, longitudinal vehicle dynamics and planetary gear dynamics.

The grounding clutch is connected with the carrier gear, so its torque can be calculated by the applied clutch pressure (P_{clu}) and the carrier speed, which is equal to the engine speed (ω_e). We focus on finding the optimal clutch pressure command in this paper, so the hydraulic dynamics of the clutch is ignored. Few of the engine-start studies reviewed in the first section account for the transient engine torque though it is really important for the engine start process. Therefore, in order to characterize the transient behavior of the powertrain during the engine start, an instantaneous engine model is required, instead of the common simplified mean value engine model which is not sufficient to represent the dynamic characteristics. The internal torque of the PG can be calculated through planetary gear model. Then, the vehicle dynamics can be determined by the motor torque (T_m) and the internal force of the PG (T_{rim}). The assumptions and the most related model equations are described in following sections.

Engine Torque Model

In order to obtain the fluctuations of engine output torque, it is necessary to develop a multi-cylinder instantaneous engine model including the intake manifold, the in-cylinder thermodynamics, and the kinematics of the crankshaft drive. Currently, great effort has been made to develop an engine model to predict the combustion and the engine output torque accurately. And a great improvement has been achieved [13, 14]. However, these models are often high-order and time consuming, which make them not recommended for control applications. A simplified engine model is introduced to compute the instantaneous engine torque by the cylinder pressure, which is calculated by a single-zone thermodynamics model. Basically, the engine output torque consists of three parts: the indicated torque, the reciprocating inertial torque and the frictional torque.

$$T_{eng}(\theta_E) = T_{ind}(\theta_E) + T_{ine}(\theta_E) + T_f(\theta_E)$$

(1)

Fig. 5 shows a simple block diagram of this engine model, whose inputs are throttle percentage and the firing signal.

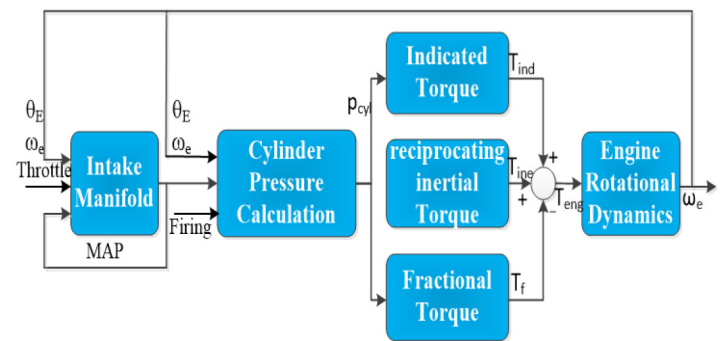


Figure 5. the block diagram of the engine model

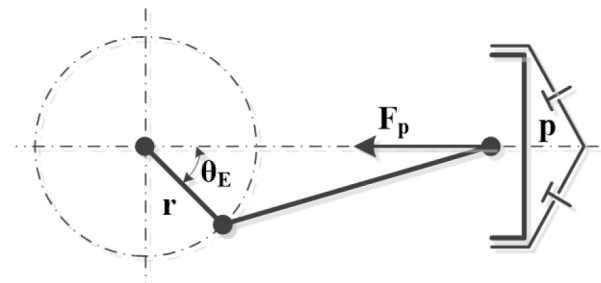


Figure 6. kinematic diagram of the engine crank-slide mechanism

Kinematics of the Crankshaft Drive

The movement of the piston will significantly determine the cylinder pressure. The position of the piston can be described by

$$s(\theta_E) = r \left\{ [1 - \cos(\theta_E)] + \frac{1}{\lambda_e} \left[1 - \sqrt{1 - \lambda_e^2 \sin^2(\theta_E)} \right] \right\}$$

(2)

where the eccentric rod relation $\lambda_e = r/l$ is the ratio of the radius of the crankshaft r and the length of the connecting rod l , $s(\theta_E)$ is the difference of the piston from the top dead center (TDC) position,