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A novel simplified model for torsional vibration analysis of a series-parallel hybrid electric vehicle

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ABSTRACT

In this study, based on our previous work, a novel simplified torsional vibration dynamic model is established to study the torsional vibration characteristics of a compound planetary hybrid propulsion system. The main frequencies of the hybrid driveline are determined. In contrast to vibration characteristics of the previous 16-degree of freedom model, the simplified model can be used to accurately describe the low-frequency vibration property of this hybrid powertrain. This study provides a basis for further vibration control of the hybrid powertrain during the process of engine start/stop.

1. Introduction

1.1. Motivations and technical challenges

The major issues currently confronted by automobile manufacturers, such as increasing oil price and regulations on pollution and CO_2 emissions, promote the development of electric vehicles (EVs) and hybrid electric vehicles (HEVs) [1–4]. Nevertheless, the use of batteries for electric vehicles must be addressed to make them competitive: long charging time, limited operating range, limited lifespan, etc. On the other hand, a hybrid electric vehicle contains two or more power sources so that it can improve fuel economy and emissions of conventional vehicles [5–7]. This is because of: (1) the engine can work in an optimal working range due to the adjusting of electric motor torque, and the engine can be shut off in some conditions (such as traffic light and downhill); (2) the energy during braking and downhill can be captured and stored in the battery through regenerative braking; (3) the engine displacement can be reduced with the same vehicle performance. Consequently, vehicle power-source hybridization has been widely adopted by automotive industry as a practical solution to increase fuel efficiency and to extend driving range [8–11].

Usually, a series-parallel (power-split) powertrain configuration is composed of two power sources connected to the powertrain: one is the combination of engine and generator using a planetary gear set to connect each other, and the other one is the electric drive system which contains motor, generator and battery [12,13]. Due to the complexity of the power-split powertrain, this kind of system has several problems, such as serious noise, vibration, harshness (NVH) issues. Especially, in order to achieve the reduction in emissions, unlike conventional vehicles where the engine only shuts off by

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Nomenclature

i_{01}	gear ratio between the small sun gear and ring
i_{02}	gear ratio between the large sun gear and ring
η_{Rd}	final ratio
J_{s1}	inertia of the small sun gear
J_{s2}	inertia of the big sun gear
J_t	inertia of the wheel
J_b	inertia of the vehicle body
J_d	equivalent moment of inertia of planetary gear set, reducer and differential
m_b	mass of vehicle
r_{Ti}	radius of the tire
θ_d	angular displacement of differential
θ_t	angular displacement of wheel
θ_b	angular displacement of vehicle body
θ_{d0}	maximum angular displacement of the differential
θ_{t0}	maximum angular displacement of the wheel
θ_{b0}	maximum angular displacement of the vehicle body
c	carrier
S1	sun gear 1
S2	sun gear 2
D_f	equivalent mass of the planetary gear set, reducer, and differential
T_i	tire
B_d	vehicle body
M'	mass matrix of compound planetary gear set
K'	stiffness matrix of compound planetary gear set
x'	displace matrix of compound planetary gear set
M	mass matrices of the hybrid driveline
K	stiffness matrices of the hybrid driveline
x	vector of generalized displacement of the hybrid driveline

ignition key off, the engine of a full hybrid system needs to be alternatively started and stopped [14–17]. As there is no clutch in a full-hybrid powertrain, the torsional vibration caused during engine start/stop process is translated to the vehicle body directly, reducing the ride comfort of the vehicle. Therefore, in order to suppress the unwanted vibration during the engine start-stop process, it is very important to analyze the torsional vibration of a full-hybrid driveline, based on which the closed-loop control can be established.

1.2. Literature review

With the aim to meet strict ride comfort requirements of customers, increasing attention has been paid by automakers and researchers to improve noise and vibration. Kuang investigated the engine start-stop NVH of a power-split hybrid electric vehicle [18]. In his research, he studied the root cause of engine start-stop NVH issues, developed a methodology and metric to gauge NVH improvement, and proposed effective counter measures to resolve NVH problems. Schulz explored the vibration behavior of a power split hybrid electric vehicle [19]. He built a linear mechanical model to research the modal analysis and the effect of the control of the driveline on the eigenvibrations. With the consideration of tire slip, he also proposed two strategies to optimize the powertrain vibrational behavior. Zhang et al. [20] established two dynamic models to explore the torsional vibration and noise characteristics of a full hybrid system. One is built using mathematical dynamic equations, and the other dynamic model is proposed in the software ADAMS. The natural frequencies and vibration modes computed from this two ways show remarkable agreements. Ma presented a quick and effective black-box method for identification and diagnosis of abnormal noise sources in an electric vehicle [21]. Canova et al. [22] researched the control problem of engine start/stop dynamics of a hybrid electric vehicle with a starter/alternator. The authors applied a model based approach to design closed-loop control for engine start/stop. After implementing the control design on the vehicle, the results showed that the belted starter/alternator is effective in starting the diesel engine quickly with low vibration and noise. Walker et al. [23] investigated the active damping of powertrains for the suppression of gear shift related transient vibrations. They developed and implemented an active strategy to manipulate output torque of electric motor post gear change through a proportional integral derivative controller. Moreover, they applied the strategy to conventional internal combustion engine and parallel hybrid vehicles, and the results show that both the conventional and hybrid powertrains are capable of successfully suppressing vibration.

Cipek et al. [24] used a unified bond graph modeling approach to model dominant dynamic effects of a two mode power-split hybrid system. Simulation models, including a quasi-static battery model, an environment model, a tire and power losses model, are established. The authors also designed a low-level electric generator speed control loop. Khodabakhshian et al. [25] proposed a simple prediction strategy and implemented it to improve fuel efficiency and drivability of a hybrid electric vehicle, which does not use any information from environment and is not computationally heavy compared to other predictive methods. Daniel et al. [26] set up a model to research an electro-mechanic braking force actuator for HEV and EV. During their study, a sliding mode control law for the braking-force actuator is derived from a sufficiently detailed model of the vehicles brake system dynamics. Their results showed that the sliding mode controller concept is superior to a standard PI controller with a setting found by the well-known T-sum tuning rule. Maalej et al. [27] explored an adaptive energy management and power-split system for a hybrid electric vehicle. Their research demonstrated that using online mass estimation improves the overall fuel consumption efficiency whilst contributing at the same tome to depth-of-discharge reduction.