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Multi-objective optimization research on the start condition for a parallel hybrid electric vehicle

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HIGHLIGHTS

- Torsional vibration of Parallel HEV start condition is studied.
- Optimum model of the Parallel HEV powertrain is established.
- Torque of the Parallel HEV powertrain is decreased by optimization method.
- Simulation optimized results are verified by experiments.

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ABSTRACT

One of the major issues for Parallel Hybrid Electric Vehicle (Parallel HEV) powertrain is the torsional vibration in the process of start condition, which is unavoidable. This article targets at reducing the damage caused by the torsional vibration with the method of Multi-Objective Optimization (MOO). The dynamic model of the parallel HEV powertrain is established by lumped mass method. Five design variables are selected from 19 parameters by the process of Design of Experiment (DOE), and are optimized by multi-objective downhill simplex optimization algorithm. Pareto Frontier is used to describe the relationship between the two objective functions, and one of the optimization data serves as the basics data for the powertrain modification. Finally, the results of optimization before and after optimization are compared by the test bench. Experimental results under the start condition show that the maximum torque of the optimized powertrain is decreased within the safe range, and the problem of shaft breaking on the originally powertrain is solved.

1. Introduction

A vehicle which uses two or more distinct types of power, such as Internal Combustion Engine (ICE) plus electric motor can be called a hybrid electrical vehicle (HEV). As the engine, motor, and battery [1] are all controlled by the Vehicle Control Unit (VEU) in a HEV, the energy of the vehicle can be used more efficiently than the ICE in the same class [2], and the battery can be kept in a better working condition than the pure electric vehicle [3]. The HEV has been considered as promising solutions to reduce fuel consumption and air pollution for ground transportation [4]. Generally, HEV can be classified into two main groups according to the way in which power is supplied: serial and parallel [5]. In the serial hybrid, only the electric motor drives the powertrain and a smaller ICE works as a generator to power the electric motor or to recharge the batteries. In the parallel hybrid, the ICE and the electric motor are connected to the mechanical transmission and can simultaneously transmit power to drive the vehicle [6]. But also facing a number of challenges due to the complexity design of the powertrain [7]. As the multi-power sources, torsional vibration is an urgent problem for Parallel HEV powertrain, and the unreasonable design may lead to resonance phenomenon happen, which possibly will cause increasingly insecure and sometimes fatal accidents in the course of start and stop conditions [8].

Modelling and optimization powertrain for vibration suppression have been proposed and studied in recent years [7]. In Ref. [9] torsional vibrations are studied in a vehicle powertrain with a four-cylinder engine and manual transmission under steady state and transient operating conditions. Extensive research conducted by Goetz et al. applies a detailed powertrain model of a front wheel-driving vehicle, using 12 degrees of freedom [10], and the dynamic effects of gear preselection through conventional hydraulically actuated cone-type synchronizers on the overall shift quality are discussed. The torque impact and its corresponding vibration problem is usually addressed via coordination torque control. Such as in reference [11], a model predictive control

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approach has been proposed and applied to adjust the torque of the motor and the clutch, so as to reduce the transmission vibration and improve the drivability. In addition, a slipping control method using the slipping speed is introduced in reference [12] for mode transition, and the torque strike during engine starting is effectively reduced. Walker, Paul D. [13] investigates the active damping of automotive powertrains for the suppression of gear shift related transient vibrations. An active control strategy for manipulating engine or electric machine output torque post gear change via a proportional-integral-derivative (PID) controller is developed and implemented. Kim [14] proposes a new approach for the mode transition control in a parallel hybrid electric vehicle with an engine clutch. The vehicle model is developed to represent the characteristics of the transient response of the target system and is used to simulate and verify the proposed control algorithms. The simulation results show the validity of the proposed control algorithms.

To sum up, the above studies reveal that researchers have analyzing and reducing the vibration of the powertrain based on numerical simulation or experimental methods, but only investigated the value of torque of the motor or engine as the solo power source. However, sometimes the power sources in Parallel HEV come from the engine and motor together. Taking into account both engine and motor in the modeling and analyzing may solve more possible problems in Parallel HEV.

The resonance is one of a common problem in Parallel HEV, which is inevitable in the start condition. Because the resonance is the interaction between excitation source (engine, motor or both), and the forced vibration part (here refers to the global and local parts of the powertrain). The global means to treat the powertrain as a whole part, and the local means to view the powertrain as consisting of several mechanical parts (such as engine, ISG motor, torsional vibration damper, clutch and so on), each of which is called the local of the powertrain. The global natural frequency is a number, but the local natural frequency are numbers. In the start condition, both of the global and local natural frequency of the powertrain is constant. When the excitation source frequency increases, and grows as the same as the global or local parts' nature frequency of the powertrain, the resonance occurs. At this time, the torque on the powertrain will be three times or even more than the torque exported by the excitation source [15]. There are some methods to solve this problem, such as transfer path method, vibration isolation method and frequency shift method. In the field of automobile powertrain, the frequency shift is a common method. The basic idea is to change the natural frequency of the excitation source or the forced vibration parts or both by modifying the stiffness matrix or the mass matrix, thus avoiding resonance occurs at the original resonance frequency. It should also be pointed out that for the powertrain, a low frequency resonance is more harmful than the high frequency resonance. Thus besides reducing the torque, it is also an important task to increase the global natural frequency of the powertrain.

Then the ensuing section of the paper presents the modeling process of powertrain.

2. Parallel HEV powertrain description

The schematic drawing of a Parallel HEV powertrain is shown in Fig. 1. The powertrain involves the local parts are as follow: four-cylinder diesel engine, flywheel, torsional vibration damper, ISG motor, spline shaft, clutch, main motor, main reducer, differential mechanism, wheels and some non-mechanical parts [16].

The "start condition", also known as "start-up condition", is a kind of driving condition for an automobile vehicle. In this condition, the speed of the vehicle grows up from zero, and the whole process of the event lasts about 1–2 s. The start condition of the hybrid electric vehicle in this paper can be explained with reference to Fig. 1 in more details: At the beginning, the speed is zero, the engine is stalled, the clutch is in a detached state. Meanwhile, the ISG motor starts to provide torque to the engine, and the torque characteristic curve is shown in Fig. 2. About 1.2 s later, the engine starts, and the clutch engages. At this time, the ISG motor stops providing torque to the engine. The engine drives the wheels to rotate through the powertrain. So far, the start condition finishes.

In the start condition, the core local parts of the powertrain are engine, flywheel, Torsional Vibration Damper (TVD), spline shaft, and the ISG motor. Table 1 represents the main original parameters of the HEV.

2.1. Excitation source 1: Engine Torque model

Fig. 2 shows the single cylinder mechanism of the engine [17]. Two major factors decide the value of the actuating frequency about the engine: cylinder gas pressure F_p, and inertia force F_j, and the sum of the two forces is F. The engine model here considers both of the two torques.

The engine torque can be described as Eq. (1).

$$T_E = F\cdot R = (F_p + F_j)\cdot R = M_P + M_j \tag{1}$$

The engine torque, which is generated by the cylinder gas press, can be described as Eq. (2).

$$M_p = F_p \frac{\sin(\alpha+\beta)}{\cos\beta} R = \frac{\pi D^2}{4} pR \frac{\sin(\alpha+\beta)}{\cos\beta} \tag{2}$$

where M_p is the engine torque, which is caused by cylinder pressure p, dimeter of the cylinder D, the crank radius R, the crank angle α, and the angle between the central line of the connecting rod and the central line of the cylinder β.

It should be noted that the engine cylinder pressure p is critical to the calculations of engine torque [18], which is measured with and without engine firing using an engine dynamometer, and the measured data is populated a look-up table for this simulation model. Fig. 3 plots single cylinder pressure against crank angle under engine start condition.

The second major cause of engine fluctuation is the inertia torque, which is generated by the reciprocating motion of the masses of the piston and connecting rod. The inertia torque can be expressed as Eq. (3).

$$M_j = F_j \frac{\sin(\alpha+\beta)}{\cos\beta} R = -m_j\omega^2 R^2 (cos\alpha + \lambda cos2\alpha) \frac{\sin(\alpha+\beta)}{\cos\beta} + m_j gR \frac{\sin(\alpha+\beta)}{\cos\beta} \tag{3}$$

In Eq. (3), M_j is the sum of inertia and gravity, m_j is the mass of the reciprocating unit, ω is the crank's angular velocity, λ is the ratio of the crank radius to length of connecting rod, and g is the gravity coefficient.

2.2. Excitation source: ISG Torque model

The role of ISG is to trigger the internal combustion engine start automatically, and the ISG's output torque function is determined by the control strategy. Thus, the characters of the ISG's output torque curve is constant. Fig. 4 shows the time domain diagram of the ISG' output torque.

The time of the startup process lasts 1.5 s. During this period, the torque of the ISG grows from zero up to 350Nm, and then decreases to zero immediately.

2.3. Powertrain

The application of lumped mass method for powertrain makes use of all of powertrain characteristics, in terms of stiffness, rotation inertia and damping coefficient, in conjunction with physical layout to produce representative models for different powertrain configurations. To