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Diesel engine torque ripple reduction through LPV control in hybrid electric vehicle powertrain: Experimental results

S. Cauet*, P. Coirault, M. Njeh

University of Poitiers, Laboratoire d'Informatique et d'Automatique pour les Systemes, 2 rue Pierre Brousse, 86022 Poitiers, France

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A B S T R A C T

This paper presents a case of persistent harmonic active control for an HEV (Hybrid Electric Vehicle) powertrain. The active control is adapted for a hybrid powertrain consisting of a one-cylinder diesel engine, coupled with a PMSM (Permanent Magnet Synchronous Machine). The PMSM assures the propulsion of the vehicle, as in conventional mild-hybrid electrical vehicles. In addition, it provides speed ripple reductions of the diesel engine. Due to the HEV speed variation, the active control must match this variation. The speed is introduced as a parameter in order to devise an LPV (linear parameter varying) control strategy. The suitability of LPV control for engine torque ripple reduction is demonstrated through a torque control implementation of the PMSM. The control strategy uses the internal model principle of multi-sinusoidal persistent disturbances. The controller is designed to involve several steps, including LMI-based (Linear Matrix Inequalities) optimization. The results show that, for the first and second orders of the ripple, speed oscillations can be reduced when the speed varies. An industrial test bed is used to validate the effectiveness of the approach and the power consumption of the strategy is analyzed.

1. Introduction

The Hybrid Electric Vehicle (HEV) represents one of the most plausible solutions to the problem of reducing gaseous pollution, as well as to that of saving energy. A lot of solutions have been proposed, for example the stop and start operation, see Bishop et al. (2007). These vehicles achieve significant benefits in terms of fuel economy, but weaknesses are still present, such as vibration, combustion instability and response delay at every engine restart. A lot of work has been done on the control of spark ignitions with the aim of attenuating vibration and combustion instability: see Zhang, Shen, and Marino (2010) and Ohn, Yu, and Min (2010). In the conventional internal combustion engine, the periodic fuel combustion in the cylinders and masses of the oscillating moving parts, in particular the piston, result in pulsing engine torque. This affects the powertrain life span, and causes increased noise, vibration and reduction in the drivers' comfort, see Chauvin et al. (2004).

In this paper, the elimination of torque ripples in the diesel engine is addressed. One way of reducing these ripples is to use a passive solution such as the flywheel. In this case, the solution is neither optimized at lower speeds nor when the speed varies. In an HEV configuration, an electric motor (in most cases a PMSM) provides the propulsion of the vehicle. This motor can therefore also be used to attenuate the diesel engine torque ripple. In this configuration, active crankshaft torque-ripple elimination is achieved through the synchronous machine torque control. This torque actuator reduces or eliminates the harmonic contents of the torque produced by the impulsive cylinder pressures in the diesel engine. The goal is either to reduce the flywheel mass or to control torsional vibration affecting the driveline. In Gusev, Johnson, and Miller (1997), the authors implement a solution on an alternator. The method of moment restriction is used for the controller synthesis. In this case, the speed of the thermal engine does not vary. Previous experimental studies had used observers to estimate the instantaneous torque in order to generate a reference. This reference cancels the oscillating torque, see Davis and Lorenz (2003). Other research has shown that open loop control of the electric motor reduces engine speed oscillation: see Nakajima, Uchida, Ogane, and Kitajima (2000). In order to improve this control, an adaptive closed loop control is needed. Simulations show that a harmonic activation neural network can be used to absorb the torque frequencies when using an AC machine (see Beuschel & Schroder, 1999) or a starter-generator (see Beuschel, Rau, & Schroder, 2000). However, none of the above-mentioned papers take into account the fact that speed varies. Also, the developed techniques depend on modeling the thermal engine.

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* Corresponding author. Tel.: +33 549453781; fax: +33 549454034.
E-mail addresses: sebastien.cauet@univ-poitiers.fr (S. Cauet), patrick.coirault@univ-poitiers.fr (P. Coirault).

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This modelization is quite complex. Unlike the previously cited contributions, the present paper proposes a way to control torque harmonic disturbances when the speed of the diesel engine varies. Only the mechanical equations are needed and only one controller is designed for all the harmonics.

An novel approach to asymptotic rejection of non-stationary disturbances is used. An important outcome of these research efforts is the definition of a system using the internal model principle. The exact asymptotic regulation typically requires the replication of the dynamics of the disturbance generating exo-system in the feedback loop. This in turn requires a structured controller divided into two parts: a suitably constructed copy of the exo-system that generates the considered reference/disturbance signals, and an accompanying controller to stabilize the system. Some solutions were provided in Koroglu and Scherer (2007, 2008) on basic vibration problems. In order to design an LPV controller, an LFT description is used. This approach allows the controller synthesis to be formulated independent of the parameters. This approach has been applied in Njeh, Cauet, and Coirault (2011). Another simple way is to consider a polytopic representation of the system. Such a representation is used in this paper. Experimental results are performed on a diesel HEV platform. Another intended contribution of this work is in adapting an LPV control approach to a hybrid powertrain setup (combining a 15 kW electric motor with a 30 kW diesel mono-cylinder engine). The electrical power consumption is ascertained.

The paper is organized as follows. In the second section the problem is formulated in the form of a statement. Then, an HEV powertrain model is proposed. This model describes the diesel HEV platform at the University of Poitiers. The next section describes the LPV control strategy and is followed by the section dealing with the LPV output feedback controller design. Before the conclusion, the experimental results are presented, with power consumption also being analyzed in this section.

2. The statement of the problem

In conventional combustion engines the combustion process and oscillating masses produce torque pulsation. This affects the power train life cycle and reduces the driver's comfort. In electric hybrid powertrains the integrated electric motor is used to start the engine motor or to generate propulsion. It can also control the fluctuating torque generated by the thermal engine: a second torque ripple generated in the opposite phase by the electric motor actively attenuates the primary torque fluctuation deriving from the thermal engine. The flywheel is normally used for this purpose but is not well adapted to the full range of speeds. In active control, the reversible PMSM is intended to replace this flywheel. In the present paper, an active control loop using this principle is implemented and is summarized in Fig. 1.

3. Hybrid powertrain test bed

The HEV powertrain test bench consists of a front mono-cylinder diesel engine and a parallel-flywheel type of motor/generator. The specifications are given by Tables 1 and 2. The experimental test bed is depicted in Fig. 2. An induction motor is used as load motor and dynamometer.

A mono-cylinder is used in order to improve the analysis of the combustion process. It is easy to extend the proposed approach and apply it to conventional 3 or 4 cylinder engines. As can be shown in Fig. 3, levels of torque ripple harmonics are different in both cases (Diesel engine speed is at idle).

Table 1
Hybrid powertrain specifications.

Hybrid powertrain descriptions	Specification
Diesel engine	499 cm^3 65 kW and 190 Nm
PMSM Motor/generator	15 kW, 64 Nm/2100 rpm
(IM Induction Motor) dynamometer	47 kW–1700 rpm

Table 2
Test conditions.

Injection timing	600 μs
Diesel flow	13.3 mg/injection
Rail pressure	700 bar

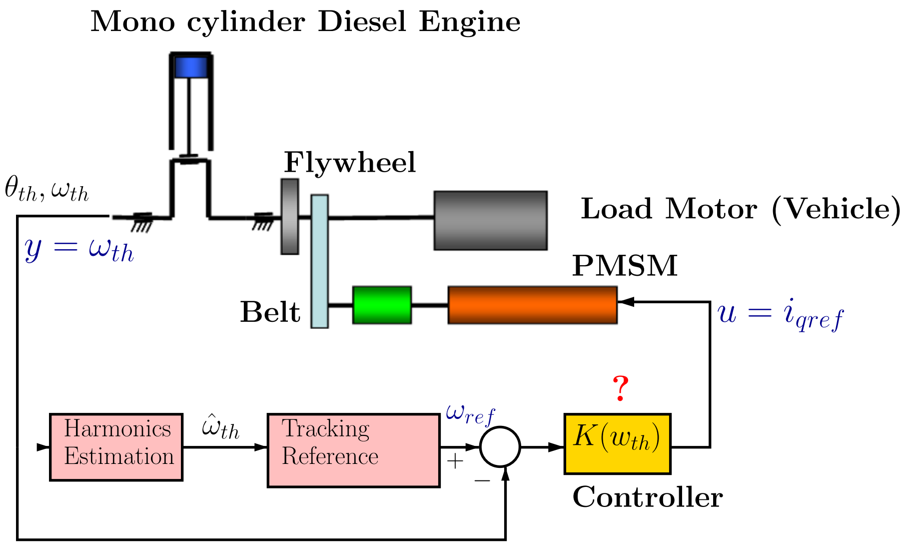

Fig. 1. Control loop.