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Model-Based Torque Shaping for Smooth Acceleration Response in Hybrid Electric Vehicles ⋆

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Abstract: Model-based design approaches can be used to help reduce the development time and cost associated with developing advanced hybrid vehicles in the automotive industry. This approach allows engineers to design more of the vehicle's control system in a virtual environment, before hardware is available to test the control software. The research presented here describes the development of a model-based approach of shaping the driver's torque request to prevent a vehicle's energy management strategy from receiving discontinuous torque request trajectories. The energy management strategy must always meet the driver's torque request, even if that torque request will cause drive quality problems during tip-in and tip-out maneuvers. Thus smoothing the torque request helps prevent the energy management strategy from receiving torque requests that have the potential to cause drive quality problems in the vehicle. A numerical model-based approach to shaping the driver's torque request is proposed here that has the capacity to handle the non-linear and discontinuous aspects of the vehicle powertrain.

Keywords: Model-Based Calibration

1. INTRODUCTION

When designing the control systems of a vehicle, one of the goals is to design the controls to allow the vehicle to have smooth accelerations in response to tip-in and tip-out maneuvers. While conventional vehicles can do this well, hybrid vehicles tend to require more calibration time to ensure their tip-in and tip-out maneuvers are smooth. This is due to two main reasons. The first is conventional vehicles contain a torque converter, which acts as a damping element to reduce any oscillations caused by sudden changes in the engine's torque. Many hybrid vehicles don't contain a torque converter due to the presence of electric machines in their drivelines. The second reason is the electric machines in a hybrid vehicle have the ability to change torque significantly faster than an engine in a conventional vehicle. The electric machines can also switch between large positive and large negative torques, while engines predominantly produce positive torque except when the vehicle is braking. These sudden changes between large positive and large negative torques, which can be triggered during tip-in and tip-out maneuvers, require more design and calibration to allow hybrid vehicles to have a smooth response to tip-in and tip-out events. One way to accomplish this smooth response is to perform an inversion on the vehicle's dynamic model. The inverted model can then take a desired acceleration trajectory and output the torque trajectory needed to accomplish the desired acceleration.

The response of the vehicle to tip-in and tip-out maneuvers is largely dependent on the position of the gear backlash in the vehicle's powertrain. When the gear backlash on a powertrain is closed, the vehicle is able to respond to a change in torque request in a smooth manner. However, if that same smooth torque request is used to accelerate the vehicle when a powertrain traverses its backlash region, there can be a significant amount of kick and jerks in the vehicle's longitudinal acceleration that the average driver would notice (Lagerberg and Egardt (2007), Schoeggl and Ramschak (2000)). An example of a tip-in event is shown in Fig. 1. Due to the gear backlash, the change in the electric machine's torque causes large oscillations in the vehicle's longitudinal acceleration that last for almost a full second and have a peak amplitude of approximately 0.75 m/s^2. The average driver would find the drive quality of this vehicle poor and may not consider purchasing it in the future (Griffin (2007)). However, one way to improve the vehicle's drive quality is to determine an effective way to shape the vehicle's torque request to achieve the desired smooth acceleration that is represented by the blue dotted line in Fig. 1.

One way to determine the ideal torque trajectory needed to give the vehicle a smooth acceleration is to solve the dynamic inverse problem analytically, where the dynamic model of the vehicle is inverted such that the ideal torque trajectory can be found by a desired acceleration shape. To solve the problem analytically multiple simplifications

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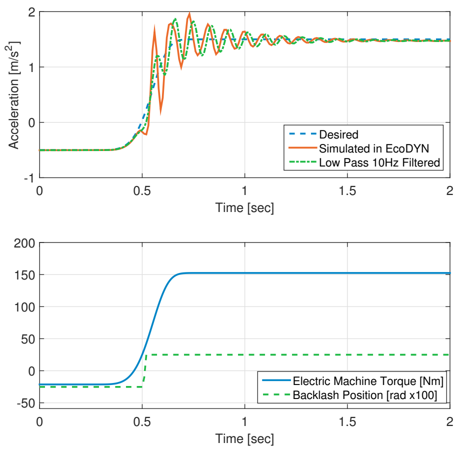

Fig. 1. Response of vehicle to change in electric machine torque with a sigmoid shape when powertrain traverses backlash regions

must be done to the dynamic model of the vehicle powertrain. These simplifications include removing all nonlinear frictional forces and discontinuities caused by physical phenomenon such as gear backlash from the model. However, gear backlash plays a large role in the tip-in and tip-out characteristics of the vehicle and must therefore be considered when finding the ideal torque trajectory to get a specific acceleration shape. Therefore, a numerical solution to the dynamic inverse problem is found using genetic algorithms.

Genetic algorithms are a method for solving an optimization problem based on the process of natural selection (Goldberg (1989), Davis (1990)). Genetic algorithms are an iterative process that starts with an initial population of potential solutions. At each iteration, or generation as it is known in genetic algorithm terminology, the fitness of each individual solution is accessed using an objective function. The individuals with the best fitness function values are used to populate the next generation of solutions using selection, crossover, and mutation operations. As the number of generations increases, the population of solutions converges towards an optimal solution. Genetic algorithms can be applied to a variety of problems that include both nonlinear and discontinuous elements. Genetic algorithms have been used before to solve seismic waveform inversion problems (Scales et al. (1992), Gerstoft (1994), Sambridge and Drijkoningen (1992), Sen and Stoffa (1992)).

The work presented in this paper uses genetic algorithms to solve the dynamic inversion problem where a desired acceleration trajectory is used to find the ideal torque trajectory needed from the vehicle's powertrain. While this numerical inversion method does not contain a control input that directly controls the backlash in a vehicle's powertrain, it can still be used to provide recommendations for how to shape a powertrain component's torque to improve the drive quality of the vehicle. The next section introduces the dynamic model of the Ohio State EcoCAR 2 vehicle used in this research. The third section introduces the genetic algorithm formulation and results. The fourth section details how the genetic algorithm results are used

Fig. 2. Ohio State EcoCAR 2 Vehicle, Photo Credit: Myles Regan

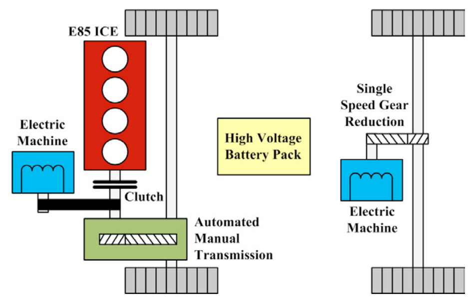

Fig. 3. Diagram of Ohio State EcoCAR 2 vehicle powertrain architecture

to develop a torque shaping algorithm that is implemented in real-time, along with some experimental results.

2. DYNAMIC MODEL OF VEHICLE

The experimental platform used for this research is a Parallel-Series Plug-in Hybrid Electric Vehicle developed by the Ohio State University for the EcoCAR 2 Competition (Bovee2012, Bovee et al. (2013), Bovee et al. (2014), AVTC (2014)). A picture of the vehicle developed by the Ohio State team is shown in Fig. 2.

A diagram of the Ohio State vehicle architecture is shown in Fig. 3. The vehicle contains a 1.8L engine that runs on E85, two electric machines that are each capable of 80kW peak power, an automated manual transmission, and an 18.9kW-hr Li-ion battery pack. The configuration of these powertrain components in the vehicle allow it to operate in a charge depleting mode, charge sustaining series mode and charge sustaining parallel mode. When the vehicle first turns on it is in charge depleting mode where both electric machines are connected to the wheels. During this time the clutch disengages the engine from the rest of the driveline and the automated manual transmission is shifted between gears. If the high voltage battery's state of charge drops below 18%, the engine is turned on and the vehicle enters one of the two charge sustaining modes. When the vehicle speed is below 56kph the vehicle is in charge sustaining series mode, where the transmission is in neutral so the front powertrain can generate electricity while the rear powertrain provides power to the wheels. When the vehicle speed is above 56kph the vehicle is in charge sustaining parallel mode, where the engine and electric machines are all connected to the wheels at the same time.

In order to do drive quality research on this vehicle, a low frequency (1-10Hz) dynamic model is developed for this research in order to allow different control strategies to be evaluated in terms of drivability and fuel economy