University of Victoria | Graduate Studies

Notice of the Final Oral Examination for the Degree of Doctor of Philosophy

of

GUANG WU

MSc (Hunan University China, 2010)
BEng (Hunan University China, 2007)

"Modeling, Control and Optimization of a Novel Multi-Mode PHEV with Hybridized Automated Manual Transmission for High Efficiency and Driveability"

Department of Mechanical Engineering

Friday, November 17, 2017
9:30 A.M.
Engineering Office Wing
Room 430

Supervisory Committee:
Dr. Zuomin Dong, Department of Mechanical Engineering, University of Victoria (Supervisor)
Dr. Curran Crawford, Department of Mechanical Engineering, UVic (Member)
Dr. Panajotis Agathoklis, Department of Electrical and Computer Engineering, UVic (Outside Member)

External Examiner:
Dr. Jorge Angeles, Mechanical Engineering, McGill University

Chair of Oral Examination:
Dr. Boualem Khouider, Department of Mathematics and Statistics, UVic

Dr. David Capson, Dean, Faculty of Graduate Studies

Abstract

This research examines various electrified and hybridized vehicles with different levels of electrification and powertrain configurations, and introduce a novel hybrid electric powertrain system based on the newly proposed Hybridized Automated Manual Transmission (HAMT) design. This new HAMT design has the advantages of regular Automated Manual Transmission (AMT) in terms of efficiency, performance, torque capacity and costs; and overcomes the drawback of poor driveability of a regular AMT due to its discontinuous torque output during gearshift. Model-based optimization, dynamics analysis, and powertrain control strategies have been introduced for a market-ready, retrofitted plug-in hybrid electric vehicle (PHEV) with a representative 8-speed HAMT. Vehicle simulations have been made to study and verify the capability and advantages of the new HAMT based hybrid electric powertrain system.

Firstly, the operation principles of various HAMT configurations are discussed. The differences of typical HAMT variations are explained using a special power-flow triangle with three ports. Based on the concept of Torque Gap Filler (TGF), a set of patent-pending HAMT system designs have been introduced and closely studied to provide continuous and stable output torque. These HAMT systems support both electric vehicle (EV) mode and hybrid electric vehicle (HEV) mode with eight variable gear ratios, and a representative eight-speed HAMT design is used to illustrate their operation principles. Torque paths at each gear, during gearshifts and operation mode transitions are defined. Among the eight forward speeds, six are independent and two are dependent on the other gears. Combinations of dog clutches at each gear are designed to guarantee the gear ratio arrangements and elimination of torque holes. The gear ratio of each gear is determined by considering the unique clutch combination of this HAMT, using the classical gear ratio design method - Progressive Ratio Steps. Due to the broader high efficiency operation region of electric motors, a model-based optimization method is used to determine the two needed gear ratios for the EV mode to achieve good fuel economy and avoid unnecessary gearshifts. Dynamic Programming (DP) is used to identify the globally optimal gear ratios, considering vehicle fuel economy for the EPA75 and Highway Fuel Economy Fuel Test (HWFET) driving cycles. The 4th and 6th gears of the HAMT are thus selected for the EV driving mode, and their gearshift schedules are determined by optimization as well. Combining the considerations for the hybrid and EV modes of the PHEV, key elements of the proposed HAMT system, including gearshift schedule, clutch combination, and gear ratios for highly efficient operation are determined.

The more challenging driveability issues during mode transition from EV to HEV and power-on gearshift with TGF during acceleration have been addressed. Both of these two operations require relatively high power/torque outputs and involve multiple powertrain components, including engine,

motor, main clutch and gearbox, within two seconds of time. A Multiple-Body Dynamics (MDB) model of the HAMT-based hybrid vehicle is built to analyze the driveline dynamics in two steady states and four transient states. Each of these states is analyzed independently, according to states of main clutch and gear selectors, and considering different phases of the TGF operation and EV-HEV mode transition. The methods for modeling the discontinuity of clutch torque and dog clutch inside the HAMT are introduced to support the subsequent vehicle powertrain modeling and control development. To identify the optimal control schemes for model transition and gearshift, the model-based optimization method for a post-transmission parallel PHEV is developed. The vehicle powertrain model was initially built using AUTONOMIE and MATLAB/Simulink with primary parameters from the retrofitted PHEV and its dSPACE ASM model. System dynamics in EV mode and hybrid mode are described as a group of state-space equations, which are further discretized into matrix form to simplify the optimization search. A DP-based global optimization method is used to identify the optimal control inputs, including engine torque, motor torque and main clutch torque. Four principles for desirable EV-HEV mode transitions are extracted based on the results of the optimization.

To model different operation modes and complicated power flows, the initial baseline powertrain system model is replaced by a customized MATLAB/SimDriveline model, and missed gearshift actuators and controller in baseline model are added to explicitly model the gearshift and mode transition processes. The gearshift schedule, which determines target gear and timing of gearshift, is determined using a reference map. To achieve good driveability, the TGF feature of the HAMT design is split into five transient and two steady phases, each corresponding to a fundamental operating mode. Control logics of upshift and downshift, as well as EV-HEV mode transition are introduced. Four principles of mode transition derived from global optimization results are introduced for powertrain system control.

Simulations of this HAMT-based PHEV have been carried out to verify the proposed HAMT design and control strategy for achieving smooth mode transition and gearshift. A number of driving scenarios are used to demonstrate the novel hybrid powertrain system's higher driveline efficiency, driveability advantage, and smooth coordination of engine, motor and main clutch operations. The research further improves the energy efficiency of HEVs/PHEVs, addresses the key driveability issues, introduces a potentially low-cost HAMT design solution with high-torque capability, and forms the foundation for further research.