Fuel economy analysis and powertrain dynamic control of a parallel hydraulic hybrid vehicle

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under the supervision of Dr. Paul Walker, Prof. Nong Zhang

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Certificate of Original Authorship

I, Shilei Zhou declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and Information Technology at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abbreviation

AMT	Automated manual transmission
BSFC	Brake specific fuel consumption
CEM	Centralized electric motor
CEV	Centralized motor drive vehicle
CHM	Centralized hydraulic motor
CTUDC	Chinese typical urban driving cycle
DP	Dynamic programming
EKF	Extended Kalman filter
EMS	Energy management strategy
HEV	Hybrid electric vehicle
HPA	High pressure accumulator
HPM	Hydraulic pump/motor
IEM	In-wheel electric motor
IEV	In-wheel drive electric vehicle
IHM	In-wheel hydraulic pump/motor
IHV	In-wheel drive electric hydraulic hybrid vehicle
LPA	Low pressure accumulator
LQR	Linear quadratic regulator
PHHV	Parallel hydraulic hybrid vehicle
PSHHV	Power-split hydraulic hybrid vehicle
SHHV	Series hydraulic hybrid vehicle
SoC	State of charge
WLTP-3	World harmonized light-duty vehicles test procedure class 3

Notation

Common symbols which are used at different places in thesis are listed below and will only be explained when they firstly appear in thesis to avoid redundancy.

M	Vehicle mass	g	Gravitational acceleration
a	Vehicle acceleration	V	Vehicle speed
δ	Vehicle rotational inertia factor	A_f	Vehicle frontal area
R_w	Tyre dynamic radius	ρ_{air}	Air density
T_e	Engine torque	C_D	Air drag coefficient
T_h	HPM torque	ϕ	Road slope
T_L	Vehicle resistant torque	f_r	Rolling resistance coefficient
T_c	Engine clutch torque	α	HPM swashplate angle
T_{bm}	Mechanical braking torque	d	HPM cylinder diameter
T_{dri}	Driver torque demand	z_c	HPM cylinder number
i_g	AMT gear ratio	R	HPM cylinder pitch radius
i_f	Main reducer gear ratio	n_h	HPM speed
i_h	HPM gear ratio	n_e	Engine speed
η_e	Engine powertrain efficiency	η_h	Hydraulic powertrain efficiency
J_e	Engine inertia	K_c	Engine clutch stiffness
J_c	Engine clutch inertia	K_o	AMT output shaft stiffness
J_i	AMT input shaft inertia	K_s	Driveshaft stiffness
J_o	AMT output shaft and driveshaft inertia	K_t	Tyre stiffness
J_f	Main reducer inertia	K_h	HPM clutch stiffness
J_v	Vehicle body inertia	C_c	Engine clutch damping
J_h	HPM inertia	C_h	HPM clutch damping
θ_e	Engine angular displacement	C_t	Tyre damping
θ_c	Engine clutch angular displacement		

θ_i	AMT input shaft angular displacement
θ_o	AMT output shaft and driveshaft angular displacement
θ_f	Main reducer angular displacement
θ_w	Wheel angular displacement
θ_h	HPM angular displacement

Abstract

This research investigates the fuel economy and powertrain vibration characteristics of a parallel hydraulic hybrid vehicle (PHHV). The main work includes: Hydraulic driving system parameter design, energy management strategy (EMS) design, powertrain vibration analysis and transient process control.

Firstly, hydraulic driving system parameters are selected based on vehicle power analysis with the Chinese typical urban driving cycle (CTUDC) which is a typical urban driving cycle. PHHV powertrain dynamics are analyzed and components such as engine, hydraulic pump/motor (HPM) and accumulator are modelled to demonstrate the PHHV working principle. PHHV fuel economy is verified by both dynamic programming (DP) optimization and practical rule-based EMS. DP optimization is conducted to explore the optimal PHHV fuel economy. The practical rule-based EMS includes driving torque allocation strategy, regenerative braking control strategy and gear shift schedule.

A lumped parameter dynamic model is built to capture the PHHV powertrain vibration characteristics including the natural frequencies and mode shapes. Then model reduction is conducted to simplify the model complexity while retaining the model fidelity in interested frequency range. The natural frequencies and mode shapes of PHHV powertrain are compared with the original vehicle powertrain which is the vehicle that PHHV refitted from. Results show that the vibration characteristics of PHHV powertrain are not significantly influenced by the addition of hydraulic driving system.

Based on the powertrain dynamic model, control strategies are designed for transient process control such as mode switching and power on gear shifting. During mode switching, engine, HPM and engine clutch are coordinately controlled. LQR based closed-loop control strategy is adopted to analyze the effect of engine clutch engaging speed on vehicle jerk, clutch frictional work and hydraulic energy consumption. HPM torque is adjusted to compensate the engine clutch torque to maintain vehicle dynamic performance. The effectiveness of the proposed mode switching control strategy is verified by simulation.

To avoid vehicle driving torque interruption during gear shifting, power on gear shifting control strategy is designed. In the control strategy, HPM compensates engine torque when engine clutch is disengaged for gear shifting. Engine clutch engagement process is also controlled by LQR controller to mitigate PHHV powertrain vibration and improve

vehicle driving comfort. Extended Kalman filter (EKF) is adopted to estimate the powertrain states required by LQR controller. Because the available HPM torque depends on its working pressure which varies a lot with different accumulator pressure state, the HPM torque compensation capability is investigated by analyzing the traction force requirement during gear shifting under typical urban driving cycles.

With the motivation of taking the advantage of high power density of HPM for in-wheel drive, a novel in-wheel drive electric hydraulic hybrid vehicle (IHV) is proposed as a case study. Its energy economy and vertical vibration characteristics are researched and compared with the centralized motor drive electric vehicle (CEV) and in-wheel drive electric vehicle (IEV).