STUDY ON TWO-SPEED TRANSMISSIONS FOR BATTERY ELECTRIC VEHICLES

by Yang Tian

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Nong Zhang

University of Technology Sydney
Faculty of Engineering and Information Technology

June 2020

CERTIFICATE OF ORIGINAL AUTHORSHIP

This research is supported by the Australian Government Research Training Program.

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of student: Production Note: Signature removed prior to publication.

Date: 24 June 2020

ACKNOWLEDGEMENT

I'd like to take this opportunity to thank the following people and organizations for their assistance and support during my candidature.

My supervisor Professor Nong Zhang, his knowledge and guidance have been invaluable, and together with co-supervisors Dr. Paul D. Walker has guided me through this research and supported my work.

My UTS colleagues, whose knowledge, advice and experience have encouraged me to do better and better, Jiageng Ruan, Wenwei Mo, Haitao Yang, Jinglai Wu, Shilei Zhou, Shengxiong Sun, Mohamed Awadallah, Jiejunyi Liang, Hanfei Wu, Boyi Xiao, and Weiwei Yang are along with me.

Most importantly my wife, Wang Jiayan, who is always by my side and help me through thick and thin, I couldn't have done this without you. Of course, my parents' advice and encouragement are indispensable.

Financial support for my project is provided by the Australian Research Council and the University of Technology Sydney (UTS).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF TERMS AND NOTATIONS

ABBREVIATIONS USED IN THESIS

EV	Electric Vehicle
BEV	Battery Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
DCT	Dual Clutch Transmission
AT	Automatic Transmission
AMT	Automated Manual Transmission
CVT	Continuously Variable Transmission
VCU	Vehicle Control Unit
SOC	State of Charge
ECE	United Nations Economic Commission for Europe (UNECE) urban driving cycle
NEDC	New European driving cycle
UDDS	Urban dynamometer driving schedule
LA-92	Los Angeles 92 / Unified cycle driving schedule
HWFET	Highway fuel economic test
JP1015	Japan 1015 emission test cycles model
UPAT	Uninterrupted Planet-gear Automatic Transmission
PAMT	Planetary Automated Manual Transmission
CITGS	The constant input torque gearshift strategy
SCOTGS	the semi-constant output torque gearshift strategy
COTGS	the constant output torque gearshift strategy

CHAPTER 3 NOTATIONS

T_i	the applied moment
J_i	the inertia
$\ddot{\theta}_i$	angular acceleration
i	the i^{th} inertia element
C	damping coefficient
K	stiffness coefficient
R	ring gear
C	carrier
SS	small sun gear
LS	large sun gear
IP	inner planet pinion
OP	outer planet pinion
OWC	one-way clutch
r_{SS}	the radius of the small sun gear
r_{IP}	the radius of inner planet pinion
r_{OP}	the radius of outer planet pinion
r_R	the radius of ring gear
r_{LS}	radius of large sun gear
i_{first}	the first gear ratio of UPAT
i_I	the gear ratio of inertia phase during gear shifting
i_{second}	the second gear ratio of UPAT
T_M	the torque of the motor
α_P	accelerator pedal position
$\dot{\theta}_M$	the motor rotational speed

k_1	the spring coefficient
c_1	the damping factor
T_I	the load on the motor
F_{LS}	the applied force
R_D	the band brake drum radius
μ_B	the Coulomb friction coefficient
α_B	the band brake wrap angle.

CHAPTER 4 NOTATIONS

T_{ef}	equivalent vehicle resistance

CHAPTER 6 NOTATIONS

LQR	linear-quadratic regulator
T_{M0}	the initial torque of the motor during torque phase
T_{C0}	the initial torque OWC during torque phase
T_{LS_Max}	the max LS brake torque
T_{M_Max}	the max motor torque in its current speed state.

CHAPTER 7 NOTATIONS

EM	electric machine
S	sun gear
P	planet gear
C	carrier
R	ring gear
GR1	gear ring 1
SH	spline hub
SL	sleeve
GR2	gear ring 2

TDP	the third-degree polynomial
FDP	the fifth-degree polynomial
SDP	the seventh-degree polynomial

ABSTRACT

Due to the shortage of fossil fuel and environment degradation, developing battery electric vehicles (BEVs) has been the irreversible trend in the automotive industry recently. Despite the long-term benefit of BEVs to customers and the environment, the initial cost and limited driving range present the significant barriers for widespread commercialization. At present, BEVs usually adopt a single driving motor with a fixed-ratio transmission in order to simplify the powertrain system; however, the performance requirements of the power battery pack and driving motor are quite high. In order to improve the efficiency of an electric driving system while meeting the requirements of vehicle driveability and reducing manufacturing costs, BEVs can be equipped with multi-speed transmissions. A two-speed transmission system appears to be suitable for BEVs in consideration of dynamic performance, energy efficiency, and cost-saving. It can improve the grade ability at low-speed and efficiency at high-speed, thereby reducing the performance requirements of the power battery pack and driving motor, which reduces the manufacturing costs to a degree.

In this thesis, two different types of two-speed transmissions are proposed. The first is a transmission that is comprised of dual-stage planet gear sets and can achieve a gear shifting without the torque interruption, called Uninterrupted Planet-gear Automatic Transmission (UPAT). The other is made up of a single planet gear set, called Planetary Automated Manual Transmission (PAMT). The proposed 2-speed UPAT takes advantage of its mechanical layout to achieve power-on gearshifts by controlling a band brake to block or unblock the one-way-clutch, which makes the gearshift control easier than

similar transmissions. Although 2-speed PAMT cannot achieve an uninterrupted torque gearshift, it has a simpler structure and an easier gearshift control system than 2-speed UPAT, and a more compact structure than traditional two-speed automated manual transmission (AMT). This thesis focus on the following six research topics: 1) mathematical modeling of 2-speed UPAT; 2) gearshift control strategies' design of 2-speed UPAT; 3) rig development and gearshift strategies' validation of two-speed UPAT; 4) optimal gear shifting control for 2-speed UPAT; 5) torque observer design for 2-speed UPAT; 6) mathematical modeling and gearshift control of 2-speed PAMT.

For two-speed UPAT study, firstly, a mathematical model is developed, including the electric motor, the proposed two-speed UPAT, the vehicle, etc. Secondly, model-based alternative power-on gearshift strategies are developed, and a torque-based gearshift closed-loop controller is proposed. The vehicle jerk and the friction work are taken as the foremost metrics to evaluate the gearshift quality. The simulation results demonstrate that all strategies can achieve power-on gearshifts. The disadvantages and advantages of these strategies are exhibited clearly, which provides beneficial knowledge and reference to the researchers engaged in the development of the transmission controller. Thirdly, to validate the simulation results, a testing rig is developed. The simulation results are well-validated by the experimental results. Fourth, to comprehensively improve the gearshift quality, optimal gearshift control tactics for the torque phase and the inertia phase are proposed to reduce the vehicle jerk and friction work within the fixed gearshift duration. And, the simulation results demonstrate that the proposed multi-objective optimal tactic for the torque phase effectively reduces the vehicle jerk and friction work, and the optimal coordinating tactic for the inertia phase decreases the friction work to a high degree.

Meanwhile, to provide unmeasurable torque information for executing the proposed optimal strategies, sliding mode theory is employed to design the torque observers which are capable of estimating the torque information sufficiently and accurately.

For two-speed PAMT study, to present the transient behaviors during the gear shifting, a detailed and original dynamical model of the electrified powertrain is developed, including an electric machine (EM), a two-speed PAMT, synchronizer mechanisms, driveline, and vehicle, etc. Afterward, the gear shifting control system is devised, and the gearshift process is orderly divided into five stages based on the proposed control strategy. Next, three alternative planning torque trajectories, i.e., the third-degree polynomial (TDP), the fifth-degree polynomial (FDP), and the seventh-degree polynomial (SDP), are proposed to control the EM torque at the first and the fifth stages of the gear shifting respectively. Then, a series of control group simulations are performed to validate which candidate trajectory can obtain the optimal gearshift quality. Simulation results demonstrate that TDP based torque trajectory is the optimal trajectory which is the capacity of not only suppressing the gear shifting jerk but also reducing shift durations. This study will also provide beneficial references for gear shifting control of clutchless automated manual transmission (CLAMT) which is widely adopted in battery electric vehicles.