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Gearshift Analysis for an Electric Vehicle with a Novel Synchronizer Mechanism

by

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Certificate of Authorship/Originality

I, Wenwei Mo, 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. This research is supported by the Australian Government Research Training Program.

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List of Publications

A proportion of Chapters 1 to 2 and a substantial proportion of Chapters 3 to 6 including Appendix A and C have been published as journal papers in Mechanical Systems and Signal Processing and Mechanism and Machine Theory.

Journals

1. **Wenwei Mo**, Paul D. Walker, Yuhong Fang, Jinglai Wu, Jiageng Ruan, and Nong Zhang, "A novel shift control concept for multi-speed electric vehicles", *Mechanical Systems and Signal Processing*, 112 (2018):171-193. DOI: https://doi.org/10.1016/j.ymssp.2018.04.017

2. **Wenwei Mo**, Paul D. Walker, and Nong Zhang,"Dynamic analysis and control for an electric vehicle with harpoon-shift synchronizer", *Mechanism and Machine Theory*, 133 (2019): 750-766. DOI: https://doi.org/10.1016/j.mechmachtheory.2018.11.018.

3. Yang Tian, Haitao Yang, **Wenwei Mo**, Shilei Zhou, Nong Zhang, and Paul D. Walker, "Optimal coordinating gearshift control of a two-speed transmission for battery electric vehicles", *Mechanical Systems and Signal Processing*, 136 (2020): 106521. DOI: https://doi.org/10.1016/j.ymssp.2019.106521

4. **Wenwei Mo**, Jinglai Wu, Paul D. Walker, and Nong Zhang, "Shift characteristics of a bilateral Harpoon-shift synchronizer for electric vehicles equipped with CLAMT", *Mechanical Systems and Signal Processing*, accepted.

Conference Proceedings

1. **Wenwei Mo**, Paul D. Walker, and Nong Zhang, "Dynamics of Dry-Clutch Engagement for Powertrain Systems with AMTs", *Proceeding: 2017 International Conference on Advanced VehiclePowertrains (ICAVP' 2017).*

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Abbreviation

MT	Manual transmission
AT	Automatic transmission
AMT	Automated manual transmission
CVT	Continuously variable transmission
DCT	Dual clutch transmission
CLAMT	Clutchless automated manual transmission
EV	Electric vehicle
MSEV	Multispeed electric vehicle
EM	Electric motor
ICE	Internal combustion engine
ECU	Electronic control unit
TCU	Transmission control unit
PSC	Power sharing control
UST	Uninterrupted shift transmission
MCS	Multi-mode controllable shifter
COWC	Controllable one-way clutch
ACL	Assist clutch
PMP	Pontryagin's minimum principle
DOF	Degree of freedom

DAC	Digital to analog converter
ADC	Analog to digital converter
DI	Digital input
DO	Digital output
PC	Personal computer
LCD	Liquid-crystal display

Notations

T_m	Motor output torque
T_{gin}	Torque of gearbox input shaft
T_{slout}	Torque of gearbox output shaft
T_{dout}	Differential drive torque
T_{hv}	Torque transmitted by the tire to vehicle
T_{load}	Load torque
T_{rg}	Torque transmitted by the torque springs
T_{pre}	Torque due to spring pre-compression
T_{sg}	Collision torque between sleeve and dog gear
T_{sr}	Collision torque between sleeve and guide ring
F_t	Tangential force acting on the chamfer surface
F_a	Axial shifting force acting on the sleeve
F'	Reaction force
J_m	Motor inertia
J_{dout}	Equivalent inertia of final drive
J_h	Equivalent inertia of Wheel hubs
J_v	Equivalent inertia of vehicle and tires
J'_s	Equivalent inertia of sleeve and sleeve hub
J'_{gin}	Equivalent inertia of input shaft

J'_{r_i}	Guide ring inertia of i-th gear
m_v	Vehicle mass
m_s	Sleeve mass
γ_1	The 1st gear ratio
γ_2	The 2nd gear ratio
γ_3	The 3rd gear ratio
γ_d	Final ratio
r_w	tire radius
N	The number of sleeve prongs
k_1	Equivalent stiffness of gearbox input shaft
k_2	Equivalent stiffness of gearbox output shaft
k_3	Equivalent stiffness of half shafts
k_4	Equivalent stiffness of tires
k_{sg}	Equivalent stiffness of collision between sleeve and dog gear
k_{sr}	Equivalent stiffness of collision between sleeve and guide ring
c_1	Damping 1
c_2	Damping 2
c_3	Damping 3
c_4	tire damping
c_m	Viscous damping
c_t	Viscous damping
c_{x_i}	Viscous damping $(i = 1, 2, 3)$
c_{sg}	Equivalent damping of collision between sleeve and dog gear

c_{sr}	Equivalent damping of collision between sleeve and guide ring
c_{rg}	Viscous damping
n	Nonlinear exponent factor
μ_s	Chamfer friction
μ_s'	Chamfer friction
μ_{sg}	Dynamic friction
θ	Angular displacement
$\dot{\theta}$	Angular velocity
$\ddot{\theta}$	Angular acceleration
x_s	Axial displacement of sleeve
$\dot{x}_s$	Axial velocity of sleeve
x_{max}	Maximum displacement
D	Variable
S_i	Variable $(i = 1, ..., 4)$
$\varDelta L$	Design parameter
θ_i	Design parameter $(i = 1, ..., 5)$
θ'	Design parameter
θ_{clr}	Parameter $(\theta_{clr} = \theta_1 - 2\theta')$
$\mathcal{L}$	Gear change signal
T_s	Torque
L_{bar}	Length of bar
G	Weight
θ_{bar}	Turning angular displacement of the bar due to the weight

q_{sg}	Relative penetration depth between sleeve and dog gear
q_{sr}	Relative penetration depth between sleeve and guide ring
$\dot{q}_{sg}$	Relative normal contact speed between sleeve and dog gear
$\dot{q}_{sr}$	Relative normal contact speed between sleeve and guide ring
R_{out}	Outside radius of the guide ring and dog gear
R_m	Mean contact radius between sleeve and guide ring tooth chamfer
β	Chamfer angle of bilateral Harpoon shift
β_1	Chamfer angle of the guide block of unilateral Harpoon shift
β_2	Chamfer angle of the external groove of unilateral Harpoon shift
Δx	Distance from guide ring's tooth tip to a certain point on its chamfer
Δx_2	Distance from dog gear's tooth tip to a certain point on its chamfer

Abstract

Multi-speed clutchless automated manual transmission (CLAMT) can offer many benefits for electric vehicles (EVs). It improves the driving efficiency and transmission performance compared to single-speed EVs. Currently, most multi-speed transmissions use conventional cone-type synchronizers for speed synchronization. However, these friction elements are a major source of inefficiency in multi-ratio gearboxes. Friction losses and heat dissipation can significantly influence transmission performance. In addition, frictional wear has a considerable impact on the service life and shifting performance of traditional synchronizers.

To overcome these drawbacks, the concept of unilateral Harpoon-shift synchronizer is introduced in the study. It aims to improve the gearboxes' efficiency and riding comfort, meanwhile, simplify the shift control logic for EVs with the multi-gear transmissions. A detailed dynamic model of the unilateral Harpoon shift is built to study the engaging performance of the proposed synchronizer. Besides, to investigate the powertrain transients, an original dynamic model of the CLAMT power-train system which integrates the Harpoon shift model is developed in the study. Also, to guarantee a smooth gear change, torque and speed profiles are designed using a modified step function for the torque control and active speed synchronization of the electric motor (EM) in EVs. Up- and down-shift simulation results verify the effectiveness of the proposed models as well as control logic.

Furthermore, to reduce the jerk during gear shifts, the Harpoon-shift torque spring stiffness in each gear is optimized via quantitative analysis. Also, the impacts of rotating inertia and speed difference on the vehicle jerks are quantitatively investigated. In addition, an experiment is conducted to study the engaging performance of the unilateral Harpoon shift and prove the effectiveness of the dynamic models.

To improve the performance of the unilateral Harpoon shift, a new concept of bilateral Harpoon shift is proposed for the multi-speed EVs equipped with CLAMTs. Then a detailed and original multi-body model of the bilateral Harpoon shift is established, aiming to capture the synchronizer's transient behavior during the engagement. In the model, the engaging process is defined as six stages, and it can cover the interacting cases between the engaging-related parts, including guide ring, sleeve, and dog gear. Then the model is integrated into the established model of the powertrain system to analyze the gearshift vibrations, allowing to investigate the engaging performance of the bilateral Harpoon shift based on the shifting shocks. Based on the integrated model, gearshift simulations are conducted and the impacts of the torque spring stiffness and tooth chamfer angle on the shifting shocks are comprehensively analyzed, and the two significant parameters are then optimized. Furthermore, comparisons are performed to demonstrate the superiority of the proposed torque profile over its counterpart based on the modified bump function. Results show that the proposed Harpoon shift can achieve high-quality gear change for EVs and meanwhile overcome the friction-related drawbacks of traditional synchronizers. Besides, the Harpoon shift greatly simplifies the shift control strategy due to its special engaging mechanism.