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Mode transition coordinated control for a compound power-split hybrid car

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ABSTRACT

With a compound power-split transmission directly connected to the engine in hybrid cars, dramatic fluctuations in engine output torque result in noticeable jerks when the car is in mode transition from electric drive mode to hybrid drive mode. This study designed a mode transition coordinated control strategy, and verified that strategy's effectiveness with both simulations and experiments. Firstly, the mode transition process was analyzed, and ride comfort issues during the mode transition process were demonstrated. Secondly, engine ripple torque was modeled using the measured cylinder pumping pressure when the engine was not in operation. The complete dynamic plant model of the power-split hybrid car was deduced, and its effectiveness was validated by a comparison of experimental and simulation results. Thirdly, a coordinated control strategy was designed to determine the desired engine torque, motor torque, and the moment of fuel injection. Active damping control with two degrees of freedom, based on reference output shaft speed estimation, was designed to mitigate driveline speed oscillations. Carrier torque estimation based on transmission kinematics and dynamics was used to suppress torque disturbance during engine cranking. The simulation and experimental results indicate that the proposed strategy effectively suppressed vehicle jerks and improved ride comfort during mode transition.

1. Introduction

Because issues of energy crisis and environmental pollution are increasingly important, hybrid electric vehicles (HEVs) are attracting considerable attention. Among various alternative powertrains, the power-split hybrid transmission [1,2] is considered to be one of the most promising configurations for HEVs. The planetary gear train (PGT) is compact, efficient, and has a high torque capacity. In addition, the power-split hybrid transmission performs as an electronic continuously variable transmission, which can result in efficient engine operation [3–5]. However, the ride comfort issue for power-split HEVs requires special consideration, as the engine is connected directly to the input shaft of the hybrid transmission through a torsional damper spring (TDS). As a low pass filter, TDS isolates high-frequency engine torque fluctuations at normal engine operation speeds when the engine is operating. Meanwhile, engine ripple torque (ERT), especially ERT that is generated at low engine speeds, is transmitted to the driveline when the engine is not operating. The TDS is excited by the ERT at these extremely low engine speeds and causes large oscillations during the car's mode transition from electric drive mode to hybrid drive mode. In addition, the discontinuous nonlinearities of TDS, such as piecewise linear stiffness, hysteresis, and preload, aggravate the transient vibration phenomenon [6,7]. Moreover, the time-

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Nomenclature

A	effective frontal area
A_p	top area of piston
B_1,B_2	wet brake clutch 1 and 2
ENG	engine
G	transfer function
I	inertia
I_{MG1},I_{MG2},I_{R1},I_L	moments of inertia of MG1, MG2, ring gear and equivelant vehicle load, respectively
J	vehicle jerk intensity
L	load of the vehicle
MG_1,MG_2	motor/generator 1 and 2
OUT	output shaft
P	pedal position
$P_{cylinder}$	cylinder pressure
P_0	enviroment pressure
PGT	planetary gear train
R_1,C_1	ring gear and carrier
S_1,S_2	small and large sun gear
TI	equivalent elastic shaft of the tire and half shaft
TDS	torsional damper spring
T	torque
T_{MG1},T_{MG2},T_{ENG}	torque of motor/generator 1, motor/generator 2 and engine, respectively
T_{S1},T_{S2},T_{C1},T_{R1}	torque of small sun gear, larger sun gear, carrier and ring, respectively
T_L	equivalent vehicle's running resistance torque
T_{WH_MG1},T_{WH_MG2}	allowable wheel torques calculated from the MG1 and MG2 torques, respectively
T_{WH_DES}	the constrained desired wheel torque
T_{MG1_DES},T_{MG2_DES}	desired MG1 and MG2 torque
T_{MG1_DAMP},T_{MG2_DAMP}	desired MG1 and MG2 damping torque
T_{R1_DES}	desired compensation torque of output shaft
T_{C1_EST}	estimated carrier torque
T_{WH_MG1min},T_{WH_MG2min}	boundary wheel torques according to the minimum MG1 torque and MG2 torque
T_{WH_MG1max},T_{WH_MG2max}	boundary wheel torques according to the maximum MG1 torque and MG2 torque
WH	wheel
c_{TI}	equivalent damping coefficient of tire and half shaft
c_{TDS}	equivalent damping coefficient of torsional damper spring
f	tire rolling resistance coefficient
i_a	final reduction gear ratio
k_{TI}	equivalent torsional stiffness of tire and half shaft
k_{TDS}	equivalent torsional stiffness of torsional damper spring
l	connection rod length
m	vehicle mass
m_p	equivalent piston mass
n	angular velocity
r	wheel radius
r_c	crankshaft radius
$r_{cylinder}$	cylinder radius
s	Laplace operator
α	crank angle
θ	angular displacement
$\ddot{\theta}_{MG1}$,$\ddot{\theta}_{MG2}$,$\ddot{\theta}_{R1}$,$\ddot{\theta}_{C1}$, $\ddot{\theta}_L$	angular acceleration of MG1, MG2, ring gear, carrier and equivelant vehicle load, respectively
ρ_1,ρ_2	gear ratio of the front and rear PGT

varying delays among sensors, controllers, and actuators in the power-split hybrid system deteriorate the control performance of the closed-loop control system [8]. Transient control during mode transition makes it rather challenging to achieve acceptable ride comfort for power-split HEVs, because doing so requires coordinated control of the engine, motors, and transmission actuators.

Existing studies on mode transition coordinated control have mainly dealt with control issues in HEVs in which the engine clutch is located between the engine and the motor [9–12], and where engine and motor power are added linearly at the input of transmission. Therefore, the key goal of controller design is to coordinate motor torque, engine torque, and clutch torque. This dynamic system functions discontinuously during mode transition, with strong non-linearities introduced by the clutch and the

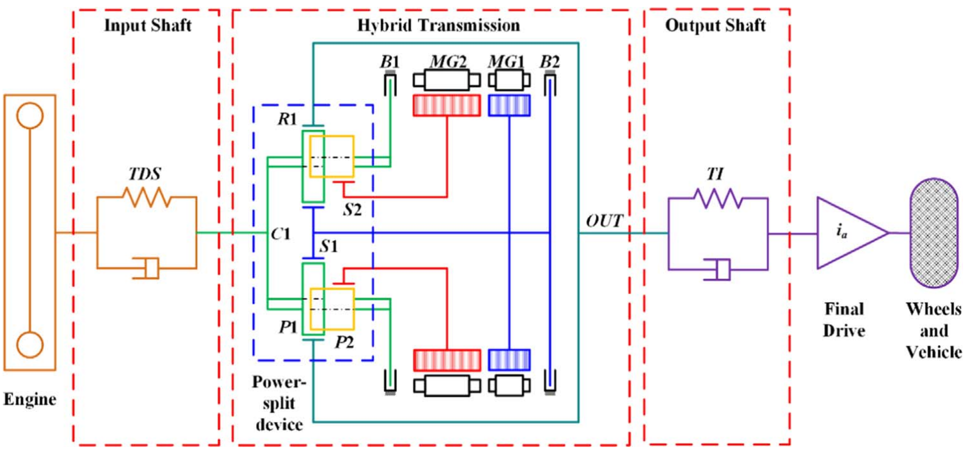

Fig. 1. Schematic diagram.