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Active damping of transient vibration in dual clutch transmission equipped powertrains: A comparison of conventional and hybrid electric vehicles

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A R T I C L E   I N F O

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A B S T R A C T

The purpose of this paper is to investigate the active damping of automotive powertrains for the suppression of gear shift related transient vibrations. Conventionally, powertrain vibration is usually suppressed passively through the application of torsional dampers in dual clutch transmissions (DCT) and torque converters in planetary automatic transmissions (AT). This paper presents an approach for active suppression of transient responses utilising only the current sensors available in the powertrain. An active control strategy for manipulating engine or electric machine output torque post gear change via a proportional-integral-derivative (PID) controller is developed and implemented. Whilst conventional internal combustion engine (ICE) powertrains require manipulation of the engine throttle, for HEV powertrains the electric machine (EM) output torque is controlled to rapidly suppress powertrain transients. Simulations for both conventional internal combustion engine and parallel hybrid vehicles are performed to evaluate the proposed strategy. Results show that while both the conventional and hybrid powertrains are both capable of successfully suppressing undesirable transients, the EM is more successful in achieving vibration suppression.

1. Introduction

Major trends in the broader automotive industry are aimed at improving the efficiency of passenger vehicles through new transmission technologies and hybridization of the powertrain. Frequently, this excludes the use of powertrain components such as hydrodynamic torque converters, which possess strong damping properties in addition to respective functional application. As a result, such vehicles are increasingly susceptible to driveline oscillations that are perceived by the driver are poor driving quality, and can be considered a source of noise vibration and harshness (NVH). The purpose of this study is to investigate the application of active damping measures for the suppression of these vibrations in the powertrain for both conventional and hybrid vehicles.

Dual clutch transmission equipped powertrain combines the power-on shifting capabilities of conventional automatics, such as planetary ATs or continuously variable transmission (CVT), with the high efficient components of manual transmissions, such as gears and synchronisers. High quality shift control is required to perform clutch-to-clutch gearshifts without loss of tractive load to the road, while still providing comfort and ride quality of the conventional AT. To increase the powertrain efficiency DCTs eliminate torque converters for the powertrain and consequently loses a significant component of system damping during

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shifting. To make use of DCTs in both conventional internal combustion engine vehicles as well hybrid electric and full electric vehicles, suppression of transient vibration resulting from gear shift is suggested to improve shift quality.

Extensive research into the control of gear shifts in dual clutch transmissions has been conducted focusing on the study of control during the shift to limit undesirable powertrain response [1–4]. This research is commonly limited by simplification of engine, hydraulic and synchroniser models to provide compact, efficient powertrain models. As a result it is frequently demonstrated that there is significant torsional vibration at the completion of shifting, though powertrain damping is sufficient to reduce vibration after a period of disturbance. The ability to provide rapid and accurate control of the engine and clutches in such research frequently does not consider the contributions of time delay in the engine through ignition of pistons or clutch hydraulics for control of such complex systems. In Walker [5] the integration of detailed hydraulic models are studied in DCT powertrain shift control, these results indicated that accuracy of clutch torque estimation is critical to shift control and the manipulation of engine torque during the final stages of shifting can lead to improvement in shift quality. However, these results still demonstrate many of the traits of a lightly damped system with limited suppression of post shift vibration.

Active powertrain damping in conventional ICE powered vehicles has been under consideration to varying degrees for some time. Berriri [6,7] develops a partial torque compensator for such vehicles that is independent of many vehicle parameters and external variables (i.e. road grade or aerodynamic drag). The compensator modifies the engine torque to suppress oscillations. One of the main limitations for suppression in conventional vehicles is identified as maintaining vehicle drivability and responsiveness; insofar that extensive variation in the engine output torque will reduce driving quality, implying that there are practical limits to the rate of suppression which may otherwise result in engine flaring or sluggish response of the vehicle. Fredriksson [8] has performed a similar study, developing PID, pole placement and Linear-Quadratic-Gaussion (LQG) controllers, with LQG being demonstrated as the most successful strategy. Bruce [9] combines feedforward and LQ feedback control and Lefebvre [10] employs H-infinity control successfully to the same issue. Fredriksson [11] and Syed [12] both apply active damping to hybrid vehicles. Syed [12] application is to a power-split HEV that utilises active control of motor torque to successfully reduce vibration to imperceptible levels.

Across each of these studies the dominant trend is to investigate powertrain oscillations resulting from transients initiated in the variation of throttle control, such as tip-in/tip-out studies of the powertrain. This paper goes beyond these studies to integrate control with power-on upshift control of the powertrain. This gear change is chosen as it the most susceptible to undesirable transients [1], in comparison to down shifts and power-off gear change.

The high efficiencies and flexibility in design of DCTs make for an ideal for application to hybrid vehicle systems. One example is for mild hybrid systems such as the ESG presented by Wagner and Wagner [13], where a 10 kW electric machine is used to improve vehicle efficiencies under high demand or low engine efficiency conditions. Alternative hybrid systems have been presented by Joshi [14] for a more complicated hybrid system employing two motors with the DCT used to control power flow of the system, providing as series–parallel type configuration. Such a design is capable of much broader operating modes for hybrid operation. Wang [15] present a hybrid powertrain for application in buses, using various drive cycles to statistically optimise design, comparisons indicate improved efficiency and mobility compared to popular integrated starter/generator designs. Kilian [16] provides the most comprehensive arrangement of hybrid DCT transmissions with electric machines capable of being placed on input shafts, primary shafts, or countershafts. Uses for these electric machines include power supply, power generation, and synchroniser assistance. Holmes [17] provides a simpler hybrid layout for a single electric machine parallel hybrid arrangement with the electric machine between dual clutches and engine, and capable of being isolated from the engine using a third clutch.

The purpose of this paper is to therefore use simulation to investigate active damping of automotive powertrains for conventional and hybrid vehicles, with particular reference to its implementation with gear shift control. Integration of active damping with shift control exceeds many current studies, which focus on tip-in/tip-out throttle control as the reference problem for study. Through application of eight degree of freedom (DOF) powertrain models of various vehicle configurations, the capability to suppress transients resulting from gear shifting is studied. This includes detailed modelling of the ICE to capture speed dependent time delay associated with piston firing [6,7], and modelling two different parallel HEV configurations.

The remainder of this paper is divided into the following sections. The first section puts forward detailed modelling of the powertrain and sub components, including the multi-body dynamic model, torque models for engine, clutches and vehicle resistance torque. DCT shift control with powertrain vibration suppression is then introduced, and discussed with reference to implementation. Then several simulations are conducted to compare shift control strategies and the impact of vibration suppression on different powertrain configurations. Finally, the paper is summarised and conclusions are made.

2. DCT equipped powertrain models

2.1. The dual clutch transmission equipped powertrain

Fig. 1 presents a basic dual clutch transmission powertrain comprising of engine, coupled clutches, transmission gear train, output drive train including differential, and wheels. The unique aspects of the DCT powertrain are the application of clutches and the arrangement of the gear train. The two clutches have a common drum attached to the input shaft from the engine, and the friction plates are independently connected to odd or even gears. For a full transmission gears 1, 3, and 5 (G1) are driven through the first clutch (C1), while clutch C2 drives gears 2, 4, 6, and R (G2). Synchronisers are denoted as S1 and S2. Thus, the transmission is