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Research paper

Dynamic modelling and simulation of a manual transmission based mild hybrid vehicle

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ABSTRACT

This paper investigates the development of a mild hybrid powertrain system through the integration of a conventional manual transmission equipped powertrain and a secondary power source in the form of an electric motor driving the transmission output shaft. The primary goal of this paper is to study the performance of partial power-on gear shifts through the implementation of torque hole filling by the electric motor during gear changes. To achieve this goal, mathematical models of both conventional and mild hybrid powertrain are developed and used to compare the system dynamic performance of the two systems. This mathematical modelling is used to run different simulations for gear-shift control algorithm design during system development, allowing us to evaluate the achievable performance and its dependency on system properties. The impact of motor power on the degree of torque hole compensation is also investigated, keeping in mind the practical limits to motor specification. This investigation uses both the output torque, vehicle speed as well as vibration dose value to evaluate the quality of gearshifts at different motor sizes. Results demonstrate that the torque hole may be eliminated using a motor power of 50 kW. However, the minimum vibration dose value during gear change is achieved using a peak power of 16–20 kW.

1. Introduction

The essential function of a modern powertrain is to deliver torque to the road-tyre interface while providing high efficiency, and excellent ride quality [1]. System design, and in particular, engine and transmission control design are the primary tools available to deliver these requirements. The control systems, including hydraulic clutch control, must provide ideal control of engine and transmission speed and torque, to achieve the best possible results during the shift period. The shift transients are the result of discontinuities in speed, torque, and inertia present during shifting. These discontinuities must be minimised to reduce the transient response of the powertrain [2]. A mild hybrid electric powertrain represents the greatest opportunity for improvement of driving comfort, shifting quality and improved driveability with low manufacturing costs. Such an architecture calls for a low-power electric motor mounted on the transmission output shaft, coupled to a controlled power source. This configuration allows for increased functionality of the powertrain along with a reduction in the torque hole during gear changes, improving driving performance.

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Primary input signals to the motor controller are; clutch position, ICE load (calculated from speed and throttle angle), and selected gear. The function of the electric machine is to eliminate or reduce the torque hole during gear changes by providing a tractive force when the clutch is disengaged, and also, provide damping for torque oscillation, particularly during gear changes and take-off (anti-jerk). The electric motor may also act as a generator under certain driving situations [3].

Major trends in the hybrid automotive industry are aimed at improving gear shift quality and increasing hybridization or electrification of the powertrain. Improved shift quality without the use of hydrodynamic torque converters is achieved through the application of precise transient clutch control technologies. Vehicles in which hydrodynamic power couplings are not used are increasingly susceptible to driveline oscillations that are perceived by the driver as poor driving quality. These oscillations can be considered a source of noise, vibration, and harshness (NVH). In these cases, damping against NVH is sourced from torsional vibration absorbers and parasitic losses in clutches, transmission components and the differential. As a consequence of eliminating the torque converter from the powertrain system damping is reduced [4,5]. However, with the use of manual transmission (MT) gear trains, a high-efficiency transmission is realised. In Hybrid Electric Vehicles (HEV) powertrains the electric machine (EM) output torque may be controlled to suppress powertrain transients rapidly. This control technique is commonly known as “anti-jerk”. Modelling and analysis for control of vehicle powertrains have been critical to the development of transmissions in recent years. Our research concerns the development of a detailed powertrain model of a front wheel drive mild hybrid electric vehicle.

This paper investigates the dynamics of a front wheel drive mild hybrid electric powertrain. A comprehensive analysis of the system with numerous degrees of freedom is proposed and the resulting sets of equations of motion are written in an indexed form that can easily be integrated into a vehicle model. Lumped stiffness-inertia torsional models of the powertrain will be developed for different powertrain states to investigate transient vibration. The major powertrain components - such as engine, flywheel, transmission, and differential - are lumped as inertia elements, interconnected with torsional stiffness and damping elements to represent a multi-degree of freedom model of the powertrain [6,7]. The generalised Newton’s second law is used to derive the models. The aim of modelling the powertrain is to identify possible improvements when using the electric drive unit. The mild hybrid powertrain is compared with a traditional manual transmission driveline. The analysis is focused on the lower gears. The reason for this is that in lower gears, the torque transferred to the drive shaft is greater, as is the deflection in the shaft. This greater deflection means the shaft torsion is higher at lower gear ratios, yielding larger oscillations. Finally, this paper deals with the role of integrated powertrain control of both engine and motor in reducing torque-hole. High-quality shift control is critical to minimising torque hole and vibration of the powertrain.

1.1. Shift process analysis

Shift process analysis is essential for MT shift quality control. The process involves the disengagement and engagement of a single clutch connecting the transmission to the power source. The shift process may be divided into three phases. The first phase involves the disengagement of the clutch and is characterised by a rapid reduction in torque transmission to zero. The second phase is the gear selection phase and is characterised by a fully disengaged clutch, torque hole as well as minor torque oscillation from the synchronisation of the selected gear. The final phase is the inertia phase and is characterised by a significant torque oscillation as the clutch slips during re-engagement. When a constant speed ratio is achieved, the speed of the powertrain is proportional to the speed of the vehicle, and the clutch is fully engaged [8]. Various factors may influence the shift process, including the magnitude of transmitted torque before and after the gear change, and the speed of clutch disengagement and engagement. Fig. 1 shows an example of actual vehicle data for half-shaft torque (with torque fill during shifts) [9].

2. Proposed mild HEV powertrain system and its modelling

Simplified engine models are popular in modelling and control applications. These include empirical models, as well as more detailed dynamic studies which use an approximation of the torque variation from piston firing for transient powertrain studies based on engine harmonics. These reduce both the model complexity and computational demand, enabling rapid simulations. The model developed herein utilises a simple empirical engine element utilising a three-dimensional lookup table. This element is inserted into two powertrain models, both of which are presented in this section. This section presents the mathematical models of each configuration, using eight degrees of freedom for the mild HEV powertrain, compared to seven degrees of freedom for a conventional powertrain. Powertrain system torques are also presented for these models, including mean engine torque, a piecewise clutch model, vehicle resistance torque, and motor torque models. Free vibration analysis is undertaken to compare the two powertrain models and demonstrate the similarities in natural frequencies and mode shapes.

2.1. Mild hybrid powertrain configuration

Fig. 2 presents a basic mild hybrid powertrain. The powertrain is a post-transmission parallel hybrid type, utilising an electric machine (EM) permanently coupled to the transmission output shaft. This configuration allows the EM to drive the wheels directly. As the motor is downstream of the transmission, it, therefore, has a fixed constant speed ratio to the wheels, via the final drive. In our transmission model, gears, 1, 2, 3, 4, and 5 (G) are connected to the input and output