Mechanical Systems and Signal Processing 93 (2017) 688–705

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Design, analysis and modeling of a novel hybrid powertrain system based on hybridized automated manual transmission

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A R T I C L E I N F O

Article history:
Received 4 September 2016
Received in revised form 16 November 2016
Accepted 20 December 2016

Keywords:
Hybrid vehicle
Electric vehicle
Transmission
AMT
Drivability
Torque-gap-filler

A B S T R A C T

Hybrid electric vehicles are widely accepted as a promising short to mid-term technical solution due to noticeably improved efficiency and lower emissions at competitive costs. In recent years, various hybrid powertrain systems were proposed and implemented based on different types of conventional transmission. Power-split system, including Toyota Hybrid System and Ford Hybrid System, are well-known examples. However, their relatively low torque capacity, and the drive of alternative and more advanced designs encouraged other innovative hybrid system designs. In this work, a new type of hybrid powertrain system based hybridized automated manual transmission (HAMT) is proposed. By using the concept of torque gap filler (TGF), this new hybrid powertrain type has the potential to overcome issue of torque gap during gearshift. The HAMT design (patent pending) is described in details, from gear layout and design of gear ratios (EV mode and HEV mode) to torque paths at different gears. As an analytical tool, mutli-body model of vehicle equipped with this HAMT was built to analyze powertrain dynamics at various steady and transient modes. A gearshift was decomposed and analyzed based basic modes. Furthermore, a Simulink-SimDriveline hybrid vehicle model was built for the new transmission, driveline and vehicle modular. Control strategy has also been built to harmonically coordinate different powertrain components to realize TGF function. A vehicle launch simulation test has been completed under 30% of accelerator pedal position to reveal details during gearshift. Simulation results showed that this HAMT can eliminate most torque gap that has been persistent issue of traditional AMT, improving both drivability and performance. This work demonstrated a new type of transmission that features high torque capacity, high efficiency and improved drivability.

1. Introduction

1.1. Background

With mounting concerns on air quality, climate degradation and exhaustion of fossil fuels, governments, automotive manufacturers and the research community are searching for cleaner and more efficient alternatives to pure Internal Combustion Engine (ICE) powered vehicles (ICE-V) [1–3]. Hybrid electric vehicles (HEV), powered by an ICE and one or more electric motors, are widely accepted as the most promising short to mid-term technical solution due to noticeably improved

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http://dx.doi.org/10.1016/j.ymssp.2016.12.029
0888-3270/

efficiency and lower emissions at competitive costs [4]. One important trend for hybrid vehicles is hybridization of transmission, in which motors were built into the transmission. All mainstream types of transmissions – manual transmission (MT), automatic transmission (AT), automated manual transmission (AMT), dual-clutch transmission (DCT) and continuously variable transmission (CVT) – have hybridized versions [5]. Compared to other automated transmission, AMT has additional advantages in cost, efficiency and torque capacity. However, AMT appears to be not ideal for passenger vehicles due to its undesirable drivability. Fig. 1 shows obvious torque gap (solid ellipsoid) and subsequent surging clutch torque (dashed ellipsoid) that appear during 3 gear shifts (neutral to 1st, 1st to 2nd, 2nd to 3rd). Although this duration is very short (around 1 s), sever change of acceleration deteriorates drivability severely. It is essential to find a method to avoid this problem.

In the past decade researchers from all over the world have tried to fill the torque gap (hole) by adding extra torque path to AMT via different methods. This Torque Gap Filler (TGF) function, illustrated in plot (a) of Fig. 2, can be realized via a passive or active method. In 2004, HITACHI Group showed that a torque-assist AMT can realize seamless acceleration and high efficiency comparable to MT in real car test [7]. Uninterrupted Shift Gearbox (USG) invented jointly by BMW, Getrag and LUK can fill 40–100% of torque gap, depending on gear and accelerator position [8]. However, USG as well as torque-assist AMT relies on slipping friction torque at higher relative speed to transmit ICE torque to wheels, so thermal load restricts its application on engine torque less than 250 Nm. Torque-assisted AMT using flywheel has also been researched [9].

Hybridized AMT (HAMT) offers new approaches to fill torque gap by creating an independent or semi-independent torque path from motor during gearshift. Generally, there are two ways to combine motor with AMT, which are pre-transmission and pos-transmission hybrid, shown in plot (b) of Fig. 2. Pre-transmission configuration allows both engine and motor to have variable gear ratio to better balance requirements for motor torque and speed, but motor cannot provide second torque path during gearshift; in comparison, post-transmission configuration supports the second path during gearshift for engine, but motor speed is determined by vehicle speed via a single gear, which inhibits advantages of HAMT over a wide speed range. Ford presented a post-transmission parallel hybrid equipped with its Automated Shift Manual Transmission (ASMT) [10]. Motor and final drive is connected via a fixed gear. In 2009, FEV released test result of a unique 7-speed HAMT on a demonstration vehicle based on Ford Focus ST [11–13]. This special 7H-AMT adopted a merged dual-gearbox structure with 3 parallel shafts, uniquely realizing flexible switch between pre- and post-transmission configurations at different gears. The basic idea is shown in plot (3) of Fig. 2. In March 2013, Oerlikon Graziano unveiled another post-transmission HAMT with dual gearboxes, with a 6-speed gearbox for engine and a 2-speed epicyclical gearbox for a motor of 120 kW. Like FEV's concept, it can also support variable gear ratio for motor and smooth gearshift in hybrid mode [14,15]. Basic concepts from Oerlikon Graziano can be described as plot (d) of Fig. 2.

In this paper, a representative hybrid powertrain configuration, which belongs to part of a pending patent application, is introduced in detail [16]. The HAMT-based powertrain takes advantage of pre- and post-transmission parallel hybrid configurations, whose basic idea is described in Fig. 3. This HAMT integrates a motor, main clutch and an 8-speed parallel-shaft gearbox into one unit. The gearbox based on manual gearbox has three connection ports, which are connected to engine via main clutch, motor and final drive, respectively. Directions of three arrows represent primary power flow direction, but reversed directions are also allowed. For example, the arrow between port 2 and 3 represents power flow in normal EV mode, but the arrow direction will be reversed during active braking. Through effective combinations of actuators inside gearbox, this new configuration can support very flexible operation and achieve desirable drivability and fuel economy. The port 1 is linked to port 3 directly via two gear ratios; the port 1 and port 2 are connected through three gear ratios; in addition, two gears exist between port 2 and port 3. As a result, port 1 is linked to port 3 through 8 gear ratios. The HAMT also supports EV driving mode. In EV mode, 8 gear ratios are also available for the motor (only partly used). Compared to aforementioned HAMTS, the research subject doesn't require the 2nd gearbox. In order to illustrate operation principle of this new HAMT concept, one representative 8-speed HAMT variant with 8 gear ratios for engine and up to 8 gear ratios for motor are analyzed in detail.

A hybrid vehicle with such a HAMT was built using MATLAB/SIMULINK/SimDriveline; vehicle supervisory controller and component controllers are also built based on AUTONOMIE modeling tool [17]. Section 2 covers HAMT structure and vehicle information; Section 3 shows detailed and operation in EV mode and HEV mode; Section 4 describes fundamental control

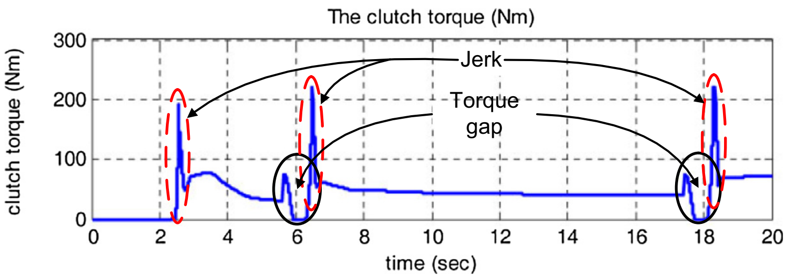

Fig. 1. AMT gear shift simulations [6].