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A novel shift control concept for multi-speed electric vehicles

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ABSTRACT

This paper proposes a novel synchronizer ‘Harpoon-Shift’ aiming at improving the comfort and efficiency of gearbox, meanwhile, simplifying the shifting control strategy for multi-speed electric vehicles. It will overcome one of the biggest shortcomings of traditional synchronizer system with frictional cone clutch.

Experiment is established to investigate the torque and speed responses during the engagement of gears pairs. Then, based on previous testing results, the relationship of the peak torque and minimum speed difference to implement gear shifting with various spring coefficients is investigated. In addition, a mathematical model of the Harpoon-Shift system is developed to simulate the engagement process. The simulation results of system transient responses are validated against the data measured on testing rig. The model is then improved to study the impact of the rotating inertia, speed and speed difference on the torsional vibration and required time of engagement. Both of the simulation and experimental results show the significant improvement of proposed synchronizer to conventional cone clutch synchronizer.

1. Introduction

The application of multi-speed transmissions in electric vehicles (EVs) continues to grow as a result of improved performance and driving efficiency in comparison to single speed EVs [1]. Traditionally, shifting and gear selection is performed with the use of friction clutches, a result of both limited controllability and high inertia of combustion engines. These friction elements are a major source of inefficiency in multi-speed gearboxes [2–4]. As electric motors are significantly more controllable that their conventional counterparts, as evidenced by paper such as [5–7], reliance on inefficient friction elements can be reduced, and even eliminated. This has resulted in the development of shift control strategies that rely on motor control rather than friction based strategies [8–10]. However, as shown in [11] these strategies cannot entirely eliminate the need for torsional vibration absorption during clutch lockup.

As established by a number of comprehensive studies on integral control of multi-speed electric vehicle (MSEV) platforms [6,12–14], and in particular those with clutchless automated manual transmissions (CLAMT) [6,12,15–16], the need for friction clutches for speed synchronization in EV shift control is reducing. Whilst these are still necessary for AT [13] and DCT [14] based platforms, CLAMTs can, in theory, achieve functional control without the use of friction clutches [5,7].

To minimize losses, the design of synchronization mechanisms is critical in applications substantially affected by system efficiency, i.e. electric vehicles [17]. Energy in an open synchroniser clutch is consumed as viscous drag. In papers such as [2,3] it is demonstrated to have a significant impact on powertrain operating efficiency. This is undesirable for multi-

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speed electric vehicle platforms that need to minimise any power losses [18]. The use of dog clutches alone, however, has limitations with "clash" type failures that occur when there is a high relative speed during engagement [4,19,20]. In [11], a controllable one-way-clutch was developed to free the use of friction elements. However, it demonstrated that substantial transients resulted from engagement as a friction clutch was used to absorb any transient shock.

This paper presents a novel gear engagement mechanism, which only consists of a torsional shock absorber and a dog clutch. It is designed to overcome any speed difference within the engaging gear set and to minimize transients during the gear shift process. Ultimately, it provides a means to select and engage gears without the use of friction clutches. The prototype demonstrated in this research offers a unique technique for overcoming issues arising from high relative speeds during engagement. This mechanism relies on relative speed difference between sleeve hub and target gear and must ensure the hub is faster than the target gear to achieve engagement. Fig. 1 presents a cross-section view of the proposed novel synchronizer in this study. It consists of input and output shafts (No. 8 and 1), sleeve (No. 6) and sleeve hub (No. 7), and guide ring (No. 2) and springs (No. 9) as the main components for actuation. As detailed extensively in the remained of this paper, this actuator relies on the use of the primary traction motor to synchronise its speed toward designed threshold. It uses the integral torsion springs to absorb residual relative motion followed by locking the target shaft to the transmission, engaging the desired gear and allowing the delivery of traction load to the wheel.

In summary, this study proposes a novel actuation device for the gears engagement in multi-speed EVs. The remainder of this paper is divided into (ii) details of the proposed synchronizer, gear shift control, (iii) mathematical model of engagement (iv) simulation results, and analysis of rotating inertia, speed and speed difference on torsional vibration, (v) rig setup, variables analyzing, and experimental results, and finally, (vi) conclusions drawn from these results.

2. Prototype concept

In MSEV platforms where speed control of the traction motor is possible for gear synchronizing, the gear engagement process could be significantly simplified. A conventional synchroniser mechanism requires (i) matching speed between a freewheeling gear and shaft by using a cone clutch, (ii) physically interlocking the gear to the shaft by using a dog clutch, and (iii) seeking no premature engagement leading to the damage of mechanical parts via the design of dog and cone clutches [4,19]. Through the application of electrical speed synchronization in MSEVs, the engagement process can be simplified. For this type of transmission, the mechanism must (i) absorb any residual relative motion between gear and shaft and (ii) physically interlock the system.

According to these requirements, a new concept synchronization mechanism is proposed. It incorporates a synchroniser groove and a sleeve to lock the gear and shaft after speed matching, and a guiding component capable to match gear and shaft speed. The speed synchronization between gear and its respective shaft is implemented by radial flexible components. The interlocking of the mechanism is implemented by angled chamfers on the synchroniser groove and the sleeve, or the

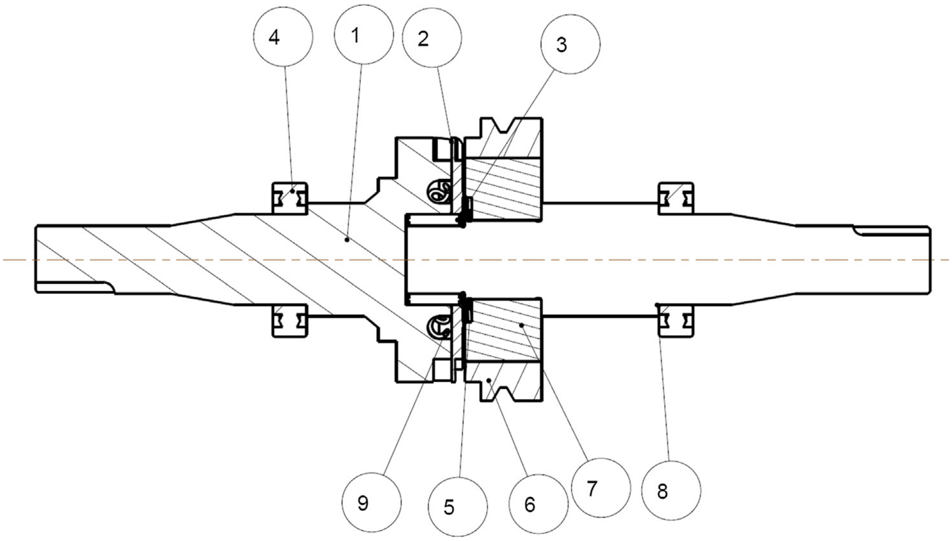

Fig. 1. Section view of 'Harpoon' shift gear engagement mechanism: (1) output shaft, (2) guide ring, (3) needle bearing, (4) deep groove ball bearings, (5) retaining ring, (6) sleeve, (7) sleeve hub, (8) input shaft, and (9) springs.