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Design and analysis of a novel multi-speed automatic transmission with four degrees-of-freedom

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ABSTRACT

With the pressing demand of reducing fuel consumption and improving driving performance, automatic transmissions (ATs) tend to have a wider ratio spread and more speeds. However, it is difficult to achieve a compact design by using only planetary gear sets (PGSs) or only parallel-axis gear pairs (PGPs). In this paper, we propose a novel multi-speed AT characterized by a combination of PGSs and PGPs on two parallel axes. All feasible clutching sequences are synthesized through a systematic procedure. Results reveal that we can obtain a nine, eleven or thirteen-speed clutching sequence by tuning the stationary ratios of PGPs. A computational model based on genetic algorithm (GA) is established to optimize the gear ratios. Within the constraints of stationary ratios and single transition shift, an optimal solution is found with a wide ratio spread. Furthermore, a matrix method is developed to analyze transmission kinematics and kinetics, which is especially suitable for computer-aided analysis of complex four degrees-of-freedom (DOFs) transmissions. Key parameters such as power flow, efficiency and clutching sequence of the proposed AT are evaluated and compared. This research may shed light upon synthesis, design and analysis of complex ATs with a wider ratio spread and more speeds.

1. Introduction

In view of fuel economy and driving performance, there has been a rapid increase in market demand for ATs with a wider ratio spread and more speeds. On the one hand, the highest gear ratio becomes smaller to improve fuel economy at high vehicle speed. On the other hand, the first gear ratio becomes larger to improve drivability in the vehicle starting and creeping process. In addition, the increasing number of speeds allows smaller gear steps to achieve more comfortable and smooth gear shift. Hence a growing number of automakers are introducing passenger cars with eight or nine-speed ATs, as a part of the continuing effort to improve drivability and fuel economy of their vehicles.

However, energy loss of ATs with high number of gear ratios may increase depending on different driving scenarios. On the highway, the vehicle usually runs at a certain speed for a long time after each gear shift. In this case, high number of gear ratios enables the engine to work in the consumption-optimal speed range at different vehicle cruising speed. The gains from the engine are

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more than the loss from gear shifts in terms of vehicle efficiency. Conversely, if the vehicle runs under urban conditions with continuous acceleration and deceleration, high frequency of gear shifts can lead to big energy loss which deteriorates the vehicle efficiency severely. By introducing direct multiple gear shifts in the shift logic, not only the shift response can be improved, but also the number of gear shifts can be reduced. Therefore, it is necessary for ATs with high number of gear ratios to have an optimal clutching sequence with most of the multi-step gear shifts being single transition shifts.

According to the relative position of engine, transmission and final drive to each other, there are two basic configurations for ATs of passenger cars: longitudinal ATs and front-transverse ATs. Longitudinal ATs are mostly planetary gear trains (PGTs) used in rear wheel drive (RWD) vehicles. The advantage of PGTs is their coaxial design which is particularly suitable for longitudinal installation. An effective coupling of several PGSs allows PGTs to achieve different gear ratios, depending on how the individual components are linked together and which components are in a fixed position. ZF and Aisin launched their six-speed longitudinal ATs in the early two thousands [1,2]. Both transmission schemes use a Lepelletier PGT which has one single planet PGS, one Ravigneaux PGS and six shifting elements. Aisin introduced its eight-speed longitudinal AT by adding one shifting element to its six-speed AT [3]. The number of PGS is unchanged. However, the PGS with single planet is replaced by the PGS with double planets. ZF developed its eight-speed longitudinal AT based on a scheme with four PGSs and five shifting elements [4,5]. This AT is a PGT with four DOFs that three shifting elements need to be engaged in each gear. It can achieve six percent fuel savings compared to the six-speed AT. Mercedes-Benz developed its own seven and nine-speed longitudinal ATs [6,7]. Currently, the nine-speed AT has the highest speed number among longitudinal ATs in mass production. However, schemes of ATs with more speeds have been disclosed in a few patents [8–10].

Comprehensive studies on the design of PGTs are available in open literatures mainly through power flow and efficiency analysis [11–19], kinematic analysis [20–24] and scheme synthesis of PGTs [25–30]. Based on graph theory, PGTs can be synthesized with the help of computer-aided design. However, the enumeration and selection of schemes become fairly difficult with the increasing number of PGSs and DOFs. Xie and Peng proposed a systemic synthesis method for the design of multi-speed PGTs with multiple operating DOFs [31,32]. Hwang introduced a precise procedure to construct usable clutch layouts for PGTs of two DOFs [33]. Compared to the enumeration methods, they find new schemes based on PGTs with two DOFs by increasing either new PGSs or new shifting elements. More PGSs and more shifting elements can achieve more speeds, but it also means a greater transmission length. This must be considered in particular for front-transverse ATs because the installation space is restricted in the front engine cabin.

Aisin introduced the first six-speed AT for FWD vehicles based on the Lepelletier PGT [34,35]. Then it developed an eight-speed front-transverse AT which realized the similar size by adopting new structure layout as shown in Fig. 1(a) [36]. In order to achieve the compactness, this AT arranged one clutch C4 inward of another clutch C3 and employed a band brake B2. Hence the transmission size did not become larger although the shifting elements increased from five to six. ZF developed a nine-speed AT

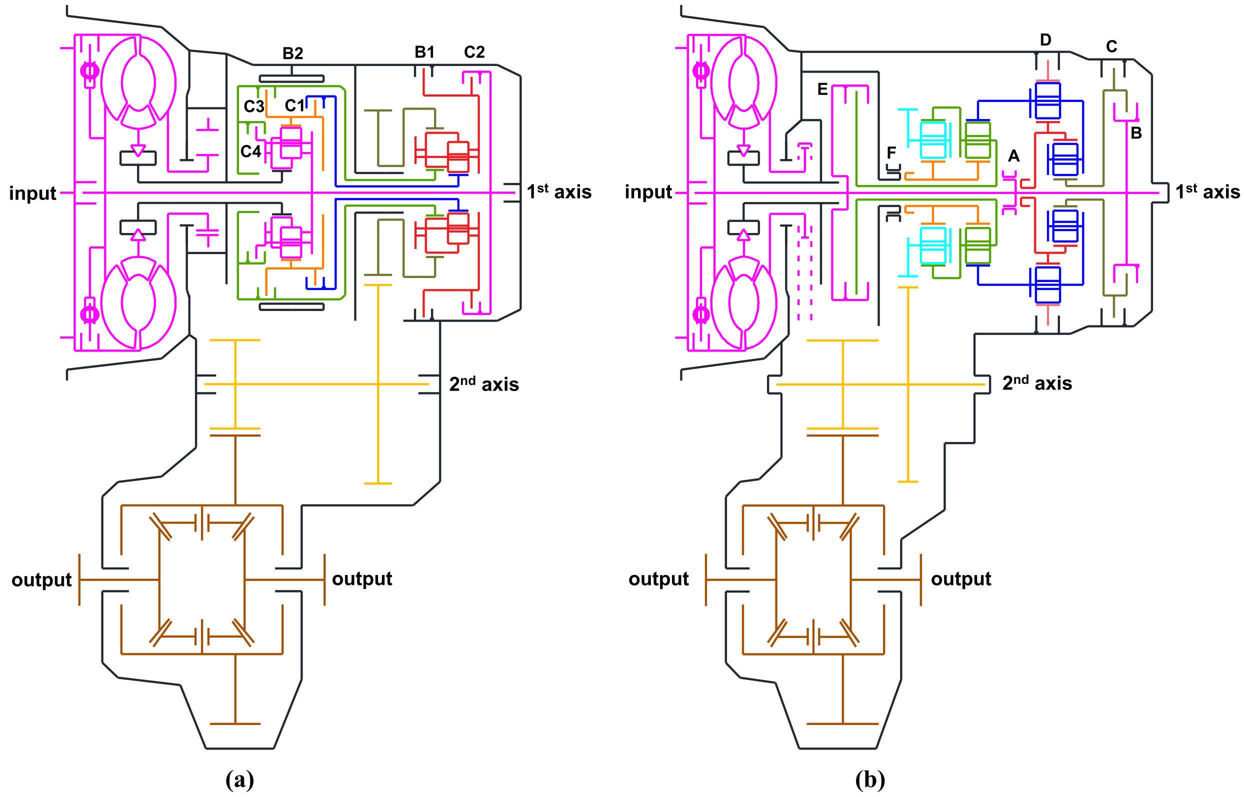

Fig. 1. (a) Scheme of the Aisin eight-speed front-transverse AT (b) Scheme of the ZF nine-speed front-transverse AT.