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Research paper

Characteristic analysis on a new hydro-mechanical continuously variable transmission system

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ABSTRACT

A new continuously variable transmission (CVT) system is proposed in this paper for the purpose of improving transmission efficiency in vehicles. The proposed system consists of a power-cycling hydro-mechanical transmission structure characterized by stepless speed regulation. In this paper, the working principle of the new CVT system is first expounded. Thereafter, the basic characteristic formulae derived in this study for speed ratio, torque, and efficiency are reported. As a significant torque ratio is obtained when the speed ratio is zero, the new CVT system provides more advantages in terms of numerous important aspects compared with other existing forms of transmission. Finally, the effect of the gear shift device, which is in a different transmission path relative to the new CVT was analyzed, and appropriate transmission structures under different operating conditions were identified.

1. Introduction

Continuously variable transmission (CVT) is an ideal form of transmission, as it has been employed in vehicles set to operate under various working conditions. Accordingly, its use has considerably improved vehicle economy [1]. Vehicles equipped with CVT have a wider range of speed ratios and can adapt to different environments compared with vehicles with a stepped drive [2]. Moreover, the hydraulic pump-motor (P/M), which is representative of hydrostatic transmission, has gained wide interest owing to the small size of its hydraulic components, low weight, and the significant advantages it provides compared with other forms of stepless transmission. However, its low transmission efficiency and high cost compared with those of the stepped drive cannot be ignored. Accordingly, a hydro-mechanical CVT structure was proposed. In this transmission structure, a hydrostatic element is set parallel to a planetary gear (PG) train to improve the overall efficiency and reduce the difficulty of developing a high-power pure hydrostatic transmission [3–7].

In relation to the above, Mucino et al. suggested the concept of continuously variable power split transmission , consisting of a V-belt CVT and PG train. The input shaft delivers the input power at two locations—at the sun gear and driving pulley—and a small part of the total power through the CVT to reduce power loss. In this regard, to prescribe both the fraction of the total power flowing through the variable element and velocity ratio span for the transmission, the term “cross-over coefficient” was devised. The foregoing can be applied by means of an external gearbox, allowing the stepless span to be within the optimum range of the engine and transmission [8].

Abbreviation: CVT, continuously variable transmission; PCVT, power-cycling continuously variable transmission; PCHMCVT, power-cycling hydro-mechanical continuously variable transmission; PST, power-split transmission; PG, planetary gear; P/M, hydraulic pump-motor; GS, gear shift; C/E, engine.

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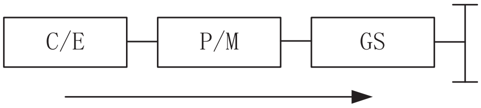

Fig. 1. Schematic of series hydraulic CVT.

Blake et al. proposed four types of hydrostatic CVT structures based on the higher speed requirements of agricultural vehicles. Moreover, the study compared the advantages and disadvantages of the four types of structures in terms of efficiency, control effort, and system complexity. Finally, an applicable model was proposed for each structure [9]. However, in the proposed structures, the system speed ratio cannot attain zero. Consequently, the full stepless transmission of the vehicle in the additive working model, which was proposed in the article, cannot be achieved.

Mantriota designed an original power split CVT system with two phases that guarantee power flow without recirculation. By using the system, the speed ratio range, output power, and efficiency have increased compared with those of a single metal belt CVT drive [10]. After that, Mantriota analyzed the power flow modes of the original power split CVT through a special test bench, and proposed the transmission ratio vales suitable for the different types of power flow in infinitely variable transmissions according to the experimental data [11,12]. Bottiglione et al. investigated the power recirculation and torque ratio of the infinitely variable transmission. The study focused on gear neutral condition, which is very useful in many applications but actually critical in terms of efficiency [13]. However, the structure reported in this article is more suitable for commercial vehicles but not for agricultural or engineering vehicles, which require more output torque.

The choice of transmission device has a significant impact on system efficiency and can result in the maximum loss of CVT under low speeds or overload. Accordingly, Macor and Rossetti implemented a design optimization for a hydro-mechanical power-split transmission based on particle swarm optimization. Compared with the traditional design method, the proposed optimization method has significant advantages, which were verified using optimization tests conducted on a small 62 kW compact loader and 180 kW agricultural tractor [14]. However, the selection of the hydrostatic components was not explained in this paper. If the choice is based on a variable pump and quantitative motor, the cost of the transmission will be lower and control will be easier.

Pettersson and Krus developed a design optimization method suitable for hydro-mechanical transmission. The method automates design and seeks the best scheme for hydraulic machinery transmission by establishing the loss model in power transmission. With the development of high-performance components, this method makes it exceptionally easy to incorporate new loss models into the design process [15].

Wang and Sun elaborated on a novel method for the design of a power-cycling variable transmission (PCVT), which is characterized by a continuously variable ratio and high efficiency over the entire working range. The method provides a set of feasible judgment criteria, basic design principles, and derived formulae for the speed ratio and efficiency characteristics of the PCVT system [16]. However, this paper only discussed a situation in which the torque converter was used as a CVT component, but did not elaborate on the other CVT components, such as the P/M.

This paper presents the newly proposed transmission structure. The discussion includes the power-cycling hydro-mechanical transmission system, and its characteristics and advantages, which were obtained from an analysis of the transmission principle and basic characteristics of the system. A comparison of the proposed system with existing forms, such as pure mechanical transmission, pure hydraulic transmission, and power-split transmission (PST) is presented as well. Moreover, new ideas and directions for the current variable speed transmission structure are provided, and a useful design reference for vehicles with a hydraulic transmission structure, such as engineering and agricultural vehicles, is proposed.

2. Working principle of the transmission system

2.1. Characteristic of the structure

The traditional series hydrostatic CVT consists of three elements: an engine (C/E), hydraulic pump-motor (P/M), and gear shift (GS) device, as shown in Fig. 1. In the figure, the thin solid line with arrows indicates the direction of the power transmission. Although this structure can achieve stepless transmission, the power goes through its low efficiency components, such as the P/M; consequently, the overall efficiency is low and the work is not ideal.

Currently, the hydro-mechanical CVT is widely used in engineering and agricultural vehicles. It generally consists of four elements: C/E, P/M, GS device, and a planetary gear (PG) train. The transmission structure is divided into input and output couplings, as shown in Fig. 2 ("$\ominus$" and "$\oplus$" indicate the power splitting point and power confluence point, respectively) [17].

In this study, a power-cycling hydro-mechanical CVT (PCHMCVT), shown in Fig. 3, is proposed. In the system, two power transmission paths—mechanical and hydraulic—use the same parallel structures, but the P/M is placed in reverse in the power-cycling path to reduce power loss. Moreover, owing to the simultaneous utilization of the power-cycling features, the entire transmission system achieves the low-speed increased-torque effect.