Design and Control Method of Power-Cycling Variable Transmission System

Dongye Sun*, HOU Wenfeng, SHI Junren, KAN Yingzhe
State Key Laboratory of Mechanical Transmissions, Chongqing University, Chongqing 40044, China
*email: dongye_sun@cqu.edu.cn

Abstract. A design theory of a power-cycling variable transmission (PCVT) system with improved transmission efficiency and continuously variable transmission characteristics was proposed for preserving the characteristics of transmission types such as the friction, hydrodynamic, and hydraulic drives. This study expounds on the structure and working principle of PCVT, analyzes its main characteristics, and describes its unique performance through a series of design examples.

1. Introduction
Friction, hydrodynamic, and hydraulic drives have unique transmission characteristics (for example, the torque converter in hydrodynamic drives has the advantages of low-speed/high-torque, continuously variable transmission, flexible transmission, and self-adaptive adjustment of speed ratio for external load), and they have been widely used in passenger vehicles, agricultural machinery, construction machinery, and military vehicles. Considering the vehicle automatic transmission system as an example, there exist classic transmission types such as automatic transmission (AT), continuously variable transmission (CVT), and hydraulic pump-motor [1].

Compared with the gear meshing drive, the efficiency of the latter transmission has defects such as a low maximum value, large high and low value variation range, and narrow range of high-efficiency area. This has been a worldwide problem for a long time that has affected the wide application of this transmission [2, 3]. Research on this transmission focuses on significantly improving the transmission efficiency of the entire transmission system for maintaining the transmission characteristics of the friction, hydrodynamic, and hydraulic drives [4-6].

For this reason, the design theory of the power-cycling variable transmission (PCVT) system is proposed, which breaks the limitations of the existing parts design from the perspective of the overall design of the transmission system and realizes efficient power transmission of the friction, hydrodynamic, and hydraulic drives. The structural composition and working principle of the PCVT system are expatiated. Using its special effects for improving efficiency, widening the speed ratio, strengthening low-speed high-torque, and reducing amplitude, the proposed design of PCVT for different service objects is realized.

2. Structure and working principle of PCVT system
Power-cycling is often a phenomenon that is avoided by the power transmission system, because it not only brings ineffective loss of cycling power, but also causes an increase in the load on the components in the main transmission path, thereby accelerating the destruction of the power transmission system.
However, in actual product designs, there are a few examples that successfully utilize power-cycling characteristics. The most famous is the closed-architecture fatigue testing platform, which can realize the long-term fatigue load test of high torque transmission parts through a few efficiency loss power compensation inputs.

In addition, although they have different structures, the continuously variable transmission system of an automobile [7] as shown in Figure 1 (a) and the transmission system of a wind turbine based on a torque converter with adjustable guide vanes [8] Figure 1 (b) have the following common characteristics.

1. Both have the phenomenon of power-cycling.
2. The metal belt and adjustable torque converter, as the typical driving elements, are not located in the main power transmission path, and function as the continuously variable transmission. In other words, the typical driving element is not used to transfer power, but to play a role in changing the speed ratio of the transmission system on the power-cycling path.
3. Equipped with a special single planetary gear mechanism to realize the split or merge of the transmitted power, and use its speed characteristic relationship to adjust the speed of the entire transmission system input or output by adjusting the typical driving element speed ratio.

By eliminating the particularity of the above drive systems and retaining their similarities, a new type of drive, i.e. PCVT, can be designed.

In addition to the basic elements such as the power source (P), typical driving element (U), and gear shifting device (S), a planetary gear train is also added to the PCVT system, as shown in Figure 2. The red line with the arrow indicates the power flow direction of the drive system, $\odot$ is the power split point and $\oplus$ is the power merge point. The driving end of the typical driving element is connected to the sun gear of the planetary gear train, while its driven end is fixed to the output shaft of the power source. The driving end of the gear shifting device is fixed to the output shaft of the power source, while its driven end is connected to the planet carrier of the planetary gear train. First, the power source is transmitted to the planet carrier through the gear shifting device. Owing to the inherent characteristic of the power split of the planetary gear train, most of the input power is transmitted by the ring gear of the planetary gear train. The rest of the power is cycled to the output shaft of the power source through a typical driving element, and then transmitted to the gear shifting device integrated with the output power of the power source.

3. Basic characteristics of PCVT system
Because of the huge difference between the structural composition and speed regulation mechanism of the PCVT system and traditional drive type, its performance has considerably changed. Its basic characteristics include efficiency, speed ratio, low-speed high-torque, and vibration-damping.

3.1. Efficiency characteristic
Assume that the planetary row of the sun gear, planet carrier, and ring gear torques are set as $M_t$, $M_p$, and
respectively; efficiency of the gear shifting device as \( \eta_k \); efficiency of the typical driving element as \( \eta_y \); torque ratio of the typical driving element as \( k_y \), whose value is the ratio of the output torque to input torque; planetary gear train parameter as \( a \), which is the ratio of the number of ring gear teeth to the number of sun gear teeth; and input and output torque of the PCVT system as \( M_i \) and \( M_o \), respectively.

If the efficiency loss between the gears of the planetary row is neglected, the equations for determining the transmission efficiency of the PCVT system can be achieved as follows:

\[
\begin{align*}
M_i : M_q : M_j &= 1 : a : (1 + a) \\
M_j &= i_k \eta_k (M_i + k_y M_i) \\
M_o &= M_q \\
\eta_y &= k_y i_y.
\end{align*}
\]

The efficiency of the PCVT system \( (\eta_{sys}) \) is as follows:

\[
\eta_{sys} = \frac{M_o n_o}{M_i n_i} = \frac{(1 + a) i_y - i_k}{(1 + a) i_y - \eta_k i_y} = \eta_k.
\]

Most of the driving power from the power source is transmitted to the output end through the efficient gear meshing transmission, and the transmission efficiency is significantly improved compared with that of the traditional direct-connected structure. Figures 3 (a) and (b) present the efficiency characteristics of power-cycling friction transmission and power-cycling hydrodynamic transmission [1], respectively.

![Figure 3. Efficiency characteristic of PCVT](image)

**3.2. Speed ratio characteristic**

Assume that the angular velocity of the sun gear, planet carrier, and ring gear of the planetary row are set as \( n_i \), \( n_j \), and \( n_q \) respectively; planetary gear train parameter as \( a \); speed ratio of the gear shifting device as \( i_k \); speed ratio of the typical driving element as \( i_y \)—owing to the particularity of the original characteristics of the torque converter, its speed ratio is the opposite of the definition of the speed ratio of other transmission mechanisms; and the input and output angular velocity of the PCVT system as \( n_i \) and \( n_o \), respectively. The equations of the transmission system speed ratio are as follows:

\[
\begin{align*}
n_i + an_q - (1 + a) n_j &= 0 \\
n_i &= i_k n_q = i_y n_i \\
n_o &= n_q.
\end{align*}
\]

To avoid infinity, the speed ratio \( i_{sys} \) of the PCVT system is defined as the ratio of the output speed to the input speed:
When the speed ratio of the PCVT system is above zero, the range of the speed ratio of the transmission system can be effectively widened, and the positive and negative can be continuously converted to realize the power commutation. The speed ratio characteristics of the power-cycling friction transmission [1] and power-cycling hydraulic transmission are shown in Figures 4 (a) and 4 (b), respectively.

3.3. Low-speed high-torque characteristic

The speed ratio of the return drive system is above zero. This causes the vehicle to encounter obstacles without shutting down the engine; it has a low-speed high-torque characteristic similar to that of the torque converter [9]. In other words, the increase in torque is caused by the PCVT and is not affected by the typical driving element used.

The torque increasing coefficient \( k_{sys} \) of PCVT is as follows:

\[
 k_{sys} = \frac{M_o}{M_i} = \frac{a_i \eta_k}{1 + a \eta_k \eta_i i_j} 
\]

3.4. Vibration-damping characteristic

The typical driving elements of the friction, hydrodynamic, and hydraulic PCVT are generally flexible. The planetary sun gear is used to flexibly connect with the typical driving elements, which can effectively reduce the vibration damping generated by the internal and external excitation of the PCVT system.

According to [9], Figure 5 (a) is the dynamic model of the roadheader’s cutting unit, which uses the hydrodynamic PCVT, and Figure 5 (b) is the dynamic meshing forces of the external (sun–planet) gear pairs in the first stage planetary gear train, denoted as \( F_{inc} \), when the roadheader suddenly encounters a high strength rock. As observed from the figure, the normal loads or pulse loads notwithstanding, the fluctuation of the dynamic meshing forces of the external (sun–planet) gear pairs in the first stage planetary gear train of the roadheader that is equipped with the PCVT is evidently lesser than that of the existing roadheader, because of the damping of the torque converter.
4. Design patterns of PCVT system

With the special effects of improving efficiency, widening speed ratio, strengthening low-speed/high-torque, and reducing amplitude, PCVT has realized the innovative design of different service objects [1, 10-16], as shown in Figure 6.

4.1. Power-cycling friction transmission

Based on the wide range of speed ratio area and continuously variable transmission of the power-cycling friction transmission system, a new configuration of the super-mild hybrid electric vehicle and plug-in hybrid electric vehicle based on the metal belt power-cycling transmission is proposed [17, 18]. For retaining the starting and stopping at idle speed function and energy recovery of the mild hybrid electric vehicle, the motor can be used to drive the vehicle independently when crawling, reversing, and entering and exiting the parking space. Compared with that of mild hybrid vehicles, the energy saving effect, which is 11.73% higher than that of fuel vehicles, is better in urban conditions [17, 18].
The auxiliary motor power (5 kW) is smaller and the number of batteries is small, which reduces the manufacturing cost of the hybrid system.

The super-mild hybrid electric vehicle is a two-shaft parallel structure, whose structure is shown in Figure 7. Table 1 lists the operation characteristics of the super-mild hybrid electric transmission, that is, the working conditions of the clutch and brake when any working mode is applied.

### 4.2. Power-cycling hydrodynamic transmission

![Figure 8. Structure of power-cycling hydrodynamic transmission system with a capacity adjustment device.](image)

The traditional hydraulic transmission system of wheel loaders is inefficient; in power matching, it prevents performance improvement during spading and transport. A power-cycling hydrodynamic transmission system with a capacity adjustment device is proposed to solve this problem [20]. The structure of the power-cycling hydrodynamic transmission system is shown in the dashed part of Figure 8. The system comprises a torque converter, planetary gear, and capacity adjustment device. It retains both the flexible transmission and advantages of the low-speed/high-torque characteristics while improving transmission efficiency.

The capacity adjustment device meets the capacity factor requirements of the hydraulic transmission system during spading and transport. A power-cycling hydrodynamic transmission system with a capacity adjustment device is proposed to solve this problem. The structure of the power-cycling hydrodynamic transmission system is shown in Figure 8. The system comprises a torque converter, planetary gear, and capacity adjustment device. It retains both the flexible transmission and advantages of the low-speed/high-torque characteristics while improving transmission efficiency.

The capacity adjustment device meets the capacity factor requirements of the hydraulic transmission system during spading and transport. A power-cycling hydrodynamic transmission system with a capacity adjustment device is proposed to solve this problem. The structure of the power-cycling hydrodynamic transmission system is shown in Figure 8. The system comprises a torque converter, planetary gear, and capacity adjustment device. It retains both the flexible transmission and advantages of the low-speed/high-torque characteristics while improving transmission efficiency.

The capacity adjustment device meets the capacity factor requirements of the hydraulic transmission system during spading and transport. A power-cycling hydrodynamic transmission system with a capacity adjustment device is proposed to solve this problem. The structure of the power-cycling hydrodynamic transmission system is shown in Figure 8. The system comprises a torque converter, planetary gear, and capacity adjustment device. It retains both the flexible transmission and advantages of the low-speed/high-torque characteristics while improving transmission efficiency.

The capacity adjustment device meets the capacity factor requirements of the hydraulic transmission system during spading and transport. A power-cycling hydrodynamic transmission system with a capacity adjustment device is proposed to solve this problem. The structure of the power-cycling hydrodynamic transmission system is shown in Figure 8. The system comprises a torque converter, planetary gear, and capacity adjustment device. It retains both the flexible transmission and advantages of the low-speed/high-torque characteristics while improving transmission efficiency.
such that the two types of power matching can achieve a better matching effect, and a reasonable conversion of full power matching and partial power matching of the engineering vehicle is realized.

4.3. Power-cycling hydraulic transmission

A hydraulic split/cycling hybrid drive system of a tractor is proposed to improve the transmission efficiency of the hydraulic pump-motor continuously variable transmission system of a heavy-duty tractor, widen the range of change of the transmission system speed ratio, and adopt the advantages of the low-speed/high-torque of the hydraulic cycling transmission system for heavy agricultural machinery. The speed ratio of the new system passes the zero point and has a low-speed/high-torque effect, which improves the starting/driving performance of the transmission system, widens the range of speed ratio changes, and improves the transmission efficiency of the drive system. The structure of the power-cycling hydraulic transmission is shown in Figure 10. The speed ratio characteristics of the heavy-duty tractor with power-cycling hydraulic transmission are shown in Figure 11.

5. Conclusion

This study investigates the design theory of the PCVT system, overcomes the limitation of the existing design from the perspective of the overall design of the system, and realizes efficient power transmission of the friction, hydrodynamic, and hydraulic drive types PCVT systems. The basic characteristics of the friction, hydrodynamic, and hydraulic drives of PCVT systems, such as efficiency, speed ratio, low-speed/high-torque, and vibration-damping are analyzed. Using the special effects of improving efficiency, widening speed ratio, strengthening low-speed/high-torque and reducing the amplitude of PCVT, the innovative design of PCVT for different service objects is realized.

Acknowledgments

This work was supported by the National Natural Science Foundation of China [No. 51875055].
References

[1] Wang H, Sun D. (2017) Theory and Application on Power-Cycling Variable Transmission System. J Mech Design.139(2): 24501.
[2] Murin J. (2005) Some properties of a diesel drive line with hydrodynamic torque converters of the latest generation. Mech Mach Theory; 40 (1): 99-117.
[3] Srivastava N, Haque I. (2009) A review on belt and chain continuously variable transmissions (CVT): Dynamics and control. Mech Mach Theory. 44 (1): 19-41.
[4] Rossetti A, Macor A. (2013) Multi-objective optimization of hydro-mechanical power split transmissions. Mech Mach Theory. 62: 112-128.
[5] Gomà Ayats J.R, Vivancos Calvet J, Minguella Canela J, Diego-Ayala U, Fenollosa Artes F. (2011) Power transmitted through a particular branch in mechanisms comprising planetary gear trains and other fixed or variable transmissions. Mech Mach Theory. 46 (11): 1744-1754.
[6] Macor A, Rossetti A. (2011) Optimization of hydro-mechanical power split transmissions. Mech Mach Theory. 46 (12): 1901-1919.
[7] Sun D, Qin D, Liao J. (2004) Analysis of Transmission Efficiency Characteristics of a Metal Belt and Planetary Gear Continuously Variable Transmission System. Transactions of the Chinese Society for Agricultural Machinery (05): 12-15.
[8] Snitchler G, Gamble B, King C, Winn P. (2011) 10 MW Class Superconductor Wind Turbine Generators. Ieee T Appl Supercon. 21 (3): 1089-1092.
[9] Wang H, Sun D, Qin D. (2016) A new continuously variable transmission system applied to transmission system of the roadheader's cutting unit. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 231 (19): 3590-3600.
[10] Kan Y, Sun D, Luo Y, Qin D, Shi J, Ma K. (2019) Optimal design of the gear ratio of a power reflux hydraulic transmission system based on data mining. Mech Mach Theory. 142: 103600.
[11] Li B, Sun D, Hu M, Zhou X, Liu J, Wang D. (2019) Coordinated control of gear shifting process with multiple clutches for power-shift transmission. Mech Mach Theory. 140: 274-291.
[12] Liu J, Sun D, Ye M, Liu X, Li B. (2018) Study on the transmission efficiency of electro-mechanical continuously variable transmission with adjustable clamping force. Mech Mach Theory. 126: 468-478.
[13] Zhang Q, Sun D, Qin D. (2017) Optimal parameters design method for power reflux hydro-mechanical transmission system. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering. 233 (3): 585-594.
[14] Liu X, Sun D, Qin D, Liu J. (2018) Multi-objective design optimization of power-cycling hydrodynamic mechanical transmissions. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. 233 (4): 1392-1410.
[15] You Y, Sun D, Qin D. (2019) Research on vehicle starting control based on reflux power condition. Mech Mach Theory. 134: 289-307.
[16] You Y, Sun D, Qin D. (2018) Shift strategy of a new continuously variable transmission based wheel loader. Mech Mach Theory. 130: 313-329.
[17] Dongye S, Datong Q, Hongyan W. (2002) Study on control strategy of clutch starting for car with a metal pushing belt-planetary gear continuously variable transmission system. Chinese Journal of Mechanical Engineering. 15 (1): 43-47.
[18] Dongye S, Datong Q, Hongyan W. (2002) Control strategy of a parallel hybrid car with a metal belt-planetary gear continuously variable transmission system. Chinese Journal of Mechanical Engineering. 15 (3): 199-203.
[19] Sun D, Zhuang J, Qin D, Liu Z. (2010) Simulation on the Control Strategy of a New Super-mild Hybrid Transmission System. Chinese Journal of Mechanical Engineering. 46 (01): 37-42.
[20] Kan Y, Sun D, Luo Y, Ma K, Shi J. (2019) Optimal design of power matching for wheel loader based on power reflux hydraulic transmission system. Mech Mach Theory. 137: 67-82.