

Shift Control of Power Split Continuously Variable Transmission

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Abstract. In order to study the shift control of power split continuously variable transmission (PSCVT), the integrated shift dynamic models for the set of engine, magnetic powder clutch and transmission are established based on the analysis of its configuration and working principle. The shift simulation shows that the magnetic powder clutch connecting condition can be adjusted and the shifting quality can be improved by means of controlling magnetic powders clutch field current, which at last result in the improvement of vehicle performance.

Introduction

Power Split CVT [1-3] (Power split continuously variable transmission, PSCVT) is composed by belt type continuously variable transmission device and planetary gear train with two degrees of freedom, with a suitable electrical control of magnetic powder clutch which replaces a conventional clutch, and conducts power transmission paralleled with engine with the application of power split principle [4-7]. Both the using of belt type continuously variable device to achieve CVT, and passing part of the power through the planetary gear train, PSCVT not only can reduce the load of the belt in order to solve the problem of dry-type with a lower carrying capacity, but also improve the efficiency of the transmission. Foreign research institutions and institutions also conduct related research [8-10].

Composition And Working Principle Of PSCVT

Power Split CVT design presented in this paper applies to the economic front drive car with front engine. Shown in Figure 1, in order to improve the performance of the vehicle starting and meet the need for reversing the vehicle, the transmission is designed to three operating modes: car starting mode, continuously variable transmission gears mode and reverse gear mode. In order to expand the range of continuously variable transmission, continuously variable gear is expanded into the low gear and high gear. Switching between the gears is done automatically by controlling the magnetic powder clutch and the shifting mechanism. Continuously variable gear is key running gear. The speed ratio of the continuously variable unit is adjusted by the implementing mechanism with dual motor, through the control of two motors to achieve precise adjustment of the speed ratio ^[6].

The transmission uses the car magnetic clutch as a power transmission member, which uses the magnetic powder of the soft magnetic material to form magnetic chain under the excitation current through the coil. The frictional forces, which generated by electromagnetic forces among the magnetic powder, transmit the torque to the driven member. Under the influence of the non-weak magnetizing current, the relationship between the output torque of magnetic clutch and the excitation current shows strong linear characteristics. That helps to realize easily a smooth increase in torque and allow longer time slipping. Compared with the torque converter, magnetic clutch can prevent from crawling when shifting and slip loss which always exists. So, it has higher transfer efficiency.

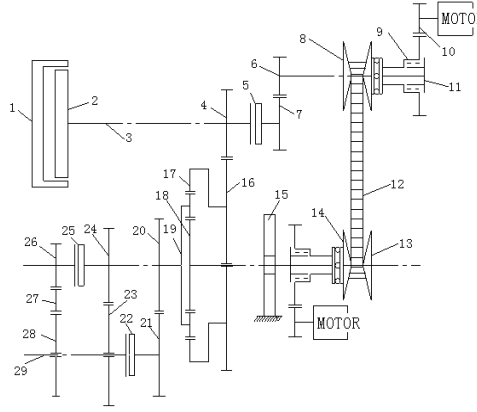


Fig.1 Structure diagram of power split continuously variable transmission

1. Engine flywheel 2. Magnetic powder clutch 3. Input shaft 4, 16. Gear ring 5. Starting mode / CVT gear mode synchronizer 6, 7. Active pulley 8. Fixed plate among active wheel 9. Screw nut 10. Motor speed reduction gear pair 11. The screw 12.V type belt 13, 14. Fixed, unfixed plate of driven pulley 15. One-way clutch 17. Gear ring 18. Sun gear 19. Planetary gear holder 20, 21. Driving and driven gear of CVT 2nd mode 22. Synchronizer of CVT 1st and 2nd mode 23, 24. Driving and driven gear of CVT 1st mode 25. Reverse gear synchronizer 26. Reverse driving gear 27. Idler wheel reverse of gear 28.The output gear of reverse gear 29. Output shaft

Under best shift rules, the vehicle automatic shift system must process of shifting timely and accurately, and speed should change smoothly without high instantaneous acceleration and deceleration in the process of shifting. If the above requirements can not be met, it will also increase the dynamic load of the transmission system, and reduce the transmission system component life, in addition to affecting the comfort. So the transmission shift control is important.

Integrated Modeling Of Engine - Magnetic Clutch - Gearbox

Power Split Automatic transmission dynamic model of the power transmission system is based on the integrated dynamic model of internal combustion engine, and magnetic clutch and transmission modeling object model, which takes into account the state before shifting and the shifting synchronization process state. The dynamics modeling assumptions: (1) no slipping of drive wheels; (2) no gaps between processes. Stages with larger effect on the shift quality are magnetic powder clutch engagement process into a new gear shift and shifting synchronization process.

Shifting 1st Gear Into Low CVT Gear:

Before shifting (clutch is engaged)

$$\begin{cases} (T_e + J_1 + \frac{J_2}{i_{PSAT1}})\dot{\omega} = T_e - \frac{T_o}{i_{PSAT1}} \\ \dot{\omega}_1 = \dot{\omega}_e \\ \dot{\omega}_2 = \frac{\dot{\omega}_e}{i_{PSAT1}} \end{cases} \quad (1)$$

$$\left\{ \begin{array}{l} \dot{\omega}_e = \frac{T_e}{J_e} \\ \dot{\omega}_1 = (-T_{sy} - \frac{T_o \alpha}{i_1 i_{Low} (1 + \alpha)}) \frac{1}{J_1 + \delta J_2} \\ \dot{\omega}_v = (T_{sy} - \frac{T_o}{i_{Low} (1 + \alpha) i_{CVU} i_2}) \frac{1}{J_v} \\ \dot{\omega}_z = \dot{\omega}_1 = (-T_{sy} - \frac{T_o \alpha}{i_1 i_{Low} (1 + \alpha)}) \frac{1}{J_1 + \delta J_2} \\ \dot{\omega}_2 = \frac{\alpha \dot{\omega}_1}{i_1 i_{Low} (1 + \alpha)} + \frac{\dot{\omega}_v}{(1 + \alpha) i_{Low} i_{CVU} i_2} \\ = \frac{\alpha}{i_1 i_{Low} (1 + \alpha)} (-T_{sy} - \frac{T_o \alpha}{i_1 i_{Low} (1 + \alpha)}) \frac{1}{J_1 + \delta J_2} \\ + \frac{1}{(1 + \alpha) i_{Low} i_{CVU} i_2} (T_{sy} - \frac{T_o}{i_{Low} i_{CVU} i_2 (1 + \alpha)}) \frac{1}{J_v} \end{array} \right. \quad (2)$$

In the starting gear, the transmission synchronizer 22 engages left, while changing into CVT gear, the transmission synchronizer 22 engages right. Kinetic equation of shifting process is shown on formula 1.

Upshift synchronization process: when the clutch is being disengaged, the synchronizer 5 engages right. Assuming that the torque T_{sy} transmitted by the synchronizer, for the left side of the synchronizer, the load torque T_0 is converted to get formula 2.

Formula (1), (2) transformed into the state equation can be obtained:

$$\left\{ \begin{array}{l} \dot{\omega} = a\omega + bu \\ y = c\omega + du \end{array} \right. \quad (3)$$

The parameters before shifting:

$$y = [\omega_e \ \omega_1 \ \omega_2]^T, \ u = [T_e \ T_o]^T, \ \omega = [\omega_e \ \omega_1 \ \omega_2], \ a = [0]_{3 \times 3}, \ d = [0]_{3 \times 2}, \ c = \text{diag}[1 \ 1 \ 1].$$

$$b = \begin{bmatrix} \frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} & -\frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} \frac{1}{i_{PSAT1}} & \frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} \\ \frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} & -\frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} \frac{1}{i_{PSAT1}} & \frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} \\ \frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} & -\frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} \frac{1}{i_{PSAT1}} & \frac{1}{J_e + J_1 \frac{J_2}{i_{PSAT1}^2}} \end{bmatrix}$$

The parameters when upshift synchronizing:

$$\omega = [\omega_e \ \omega_1 \ \omega_v \ \omega_z \ \omega_2], \ a = [0]_{5 \times 5}, \ u = [T_e \ T_{sy} \ T_o], \ c = \text{diag}[1 \ 1 \ 1 \ 1 \ 1], \ d = [0]_{5 \times 3}.$$

$$b = \begin{bmatrix} \frac{1}{J_e} & 0 & 0 \\ 0 & -\frac{1}{J_1 + \delta J_2} & -\frac{1}{J_1 + \delta J_2} \frac{1 + \alpha}{i_1 i_{Low} \alpha} \\ 0 & \frac{1}{J_v} & -\frac{1}{J_v i_{Low} (1 + \alpha) i_{CVU} i_2} \\ 0 & -\frac{1}{J_1 + \delta J_2} & -\frac{1}{J_1 + \delta J_2} \frac{1 + \alpha}{i_1 i_{Low} \alpha} \\ 0 & \frac{1}{(1 + \alpha) i_{Low} i_{CVU} i_2} - \frac{\alpha}{(J_1 + \delta J_2) i_1 i_{Low} (1 + \alpha)} & -\frac{\alpha^2}{(J_1 + \delta J_2) i_1^2 i_{Low}^2 (1 + \alpha)^2} - \frac{1}{i_2^2 i_{Low}^2 i_{CVU} (1 + \alpha)^2} \end{bmatrix}$$

Shifting Low Gear Into High Gear Of CVT Gear

When shifting low gear into high gear of CVT gear, magnetic clutch needs to be disconnect and the synchronizer engages right combination. The resulting formula is as follows:

$$\begin{cases} \dot{\omega}_e = \frac{T_e}{J_e} \\ \dot{\omega}_1 = -T_{sy3} \frac{1}{J_{v'}} \frac{(1+\alpha)i_1 i_2 i_{CVU} i_{High}}{i_1 + \alpha i_2 i_{CVU}} \\ \dot{\omega}_{z3} = \left(\frac{(1+\alpha)i_1 i_{High} T_e}{\alpha} - T_{sy3} \right) \frac{1}{J_{v'}} \\ \dot{\omega}_{v3} = (T_{sy3} - T_o) \frac{1}{J_2} \\ \dot{\omega}_2 = \dot{\omega}_{v3} = (T_{sy3} - T_o) \frac{1}{J_2} \end{cases} \quad (4)$$

In the formula the parameter with the subscript v represents the synchronizer driven end, z represents the driving side. When the CVT upshifting from low gear, the clutch must be disconnected to decelerate the sun gear as possible to the desired value. When downshifting from high gear, the clutch needs to be kept combination to improve the driven wheel speed i_{Low} .

The CVT gear downshift kinetic equation from high gear:

$$\begin{cases} \dot{\omega}_e = \dot{\omega}_1 = \left(\frac{(1+\alpha)i_1 i_{Low} T_e}{\alpha} - T_{sy3} \right) \frac{1}{J_{z'}} \frac{(1+\alpha)i_1 i_2 i_{CVU} i_{Low}}{i_1 + \alpha i_2 i_{CVU}} \\ \dot{\omega}_{z3} = \left(\frac{(1+\alpha)i_1 i_{Low} T_e}{\alpha} - T_{sy3} \right) \frac{1}{J_{z'}} \\ \dot{\omega}_{v3} = (T_{sy3} - T_o) \frac{1}{J_2} \\ \dot{\omega}_2 = \dot{\omega}_{v3} \end{cases} \quad (5)$$

The difference between downshift and upshift: the final driven gears at the moment of inertia values are different, and the rest are the same.

Transmission Dynamic Shift Simulation

When Shifting into CVT low gear from starting gear, for example, synchronization components speed curves are shown in Figure 2 and Figure 3, during the Power Split CVT upshift processes from the model simulation. Described in the two figures is a dynamic process of PSCVT upshift, two figures describe two important stages of the electronically controlled synchronizer synchronization and magnetic particle clutch synchronization during the upshift processes.

The synchronization procedure of the magnetic powder clutch requires that the vehicle speed change is smoother, and the impact degree is small, therefore the bonding process of the magnetic clutch need control. Its two control amounts include the rate of change of the initial excitation current and the excitation current of the magnetic clutch.

Before the synchronizing between driving member speed ω_z and driven member speed ω_v in electrically controlled synchronizer, the magnetic clutch is in the off state, and synchronization process of electrically controlled synchronizer needs to be completed quickly. In this process, due to the effect of inertia of the vehicle, the vehicle speed change is not obvious. After the end of the synchronization process of the electrically controlled synchronizer, magnetic clutch starts supplying power. The start time point of excitation current is shown in Figure 2, Figure 3, the magnetic clutch of the driving and driven member is in a slide-grinding process. After the synchronization point of the magnetic clutch is the end of the synchronization process, and excitation current of the magnetic powder clutch rise rapidly to the rated current.

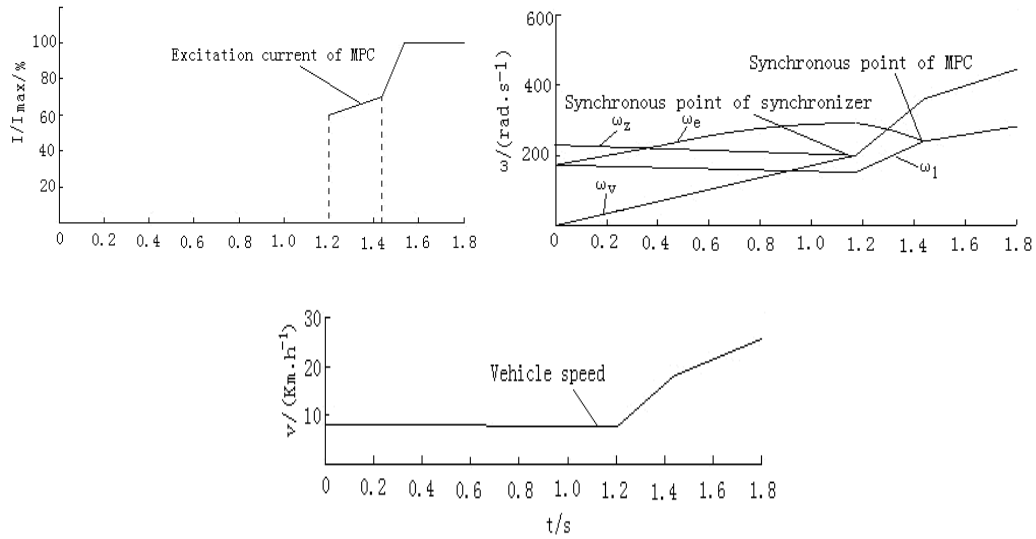


Fig2. Speed curve of shift process synchronization components (The larger initial value and growth rate of the excitation current)

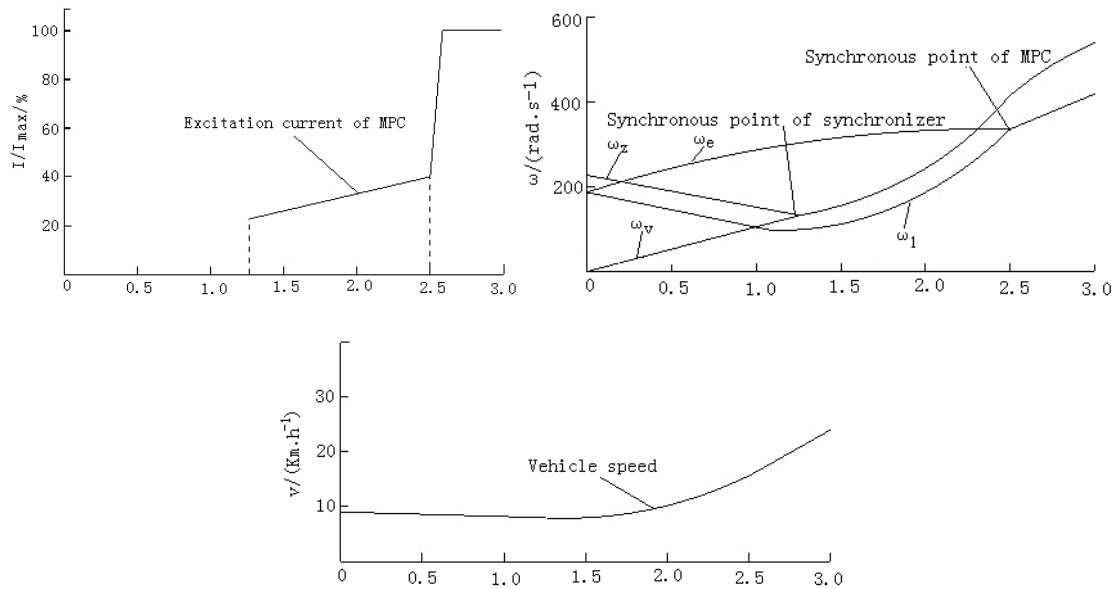


Fig3. Speed curve of shift process synchronization components (The smaller initial value and growth rate of the excitation current)

Tab1. Synchronization component characteristics in shift process

	Stable time	Fluctuation interval		Speed trend
Status1	1.45	1.20-1.40	1.40-1.45	Polyline
Status2	2.60	1.25-2.50	2.50-2.60	Gently rounded

As shown in Figure 2 and Figure 3, during the synchronizing period, the initial excitation current of the magnetic clutch is larger in Figure 2, and the change rate of the excitation current is also larger. The results are, the speed change in Figure 3 is smoother than that in Figure 2, and the impact is smaller. Synchronizing component characteristics are shown in Table 1 during the upshift process. As shown in Figure 3, the reduction of the initial excitation current and the current change rate of magnetic clutch makes synchronization time extended, which requires reasonably the size and change rate of the initial exciting current in the magnetic clutch slipping range.

Conclusion

By joint modeling of the internal combustion engine, electric control synchronizer and magnetic powder clutch during the process of shifting, in-depth analysis of the shifting process, conducts a theoretical foundation for the development of the shift control system. The simulation analyzes the speed change of the relevant parts to be synchronized in different shift stages and the effect on the shift quality by the magnetic powder clutch due to size changes in the amount of control in the process of shifting.

The study shows that the engagement state of the magnetic clutch can be adjusted to effectively improve shift quality and vehicle performance by controlling the excitation current of the magnetic clutch.

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References:

- [1] Tian Gang, Li Guang, Tian Jinyue. Characteristic Analysis of Pressure Regulator Valve of 4-speed Powered-shift Transmission [J]. Machine Tool & Hydraulics, 2012, 40(13):155-161.
- [2] Guo Xiaolin, Chen Gan, Pan Jiaping. Research on Pressure Control System of Dry Dual-clutch Transmission [J]. Machine Tool & Hydraulics, 2012, 40(13):25-28.
- [3] Li Jiangjiang, You Mingfu. Design of Automatic Transmission Hydraulic System Based on Logical Analysis [J]. Machine Tool & Hydraulics, 2011, 39(10):69-76.
- [4] Sun Dongye, Yin Yanli, Hao Yunzhi. Continuous Power Shift Control Strategy of Continuously Variable Transmission System with Reflux Power [J]. China Mechanical Engineering, 23(1):89-93
- [5] Fox Andrew J. Design and analysis of a modified power-split continuously variable transmission [D]. Morgantown, West Virginia, USA: West Virginia University, College of Engineering and Mineral Resources, 2003.20-35.
- [6] Gomez Miguel M. A Continuously Variable Power-Split Transmission in a Hybrid-Electric Sport Utility Vehicle [D]. Morgantown, West Virginia: West Virginia University, College of Engineering and Mineral Resources, 2003.40-50
- [7] Chang Siqin, Zhang Lanchun. Power Split Continuously Variable Transmission [P]. China: Utility model patents 200720033743.4, 2008-01-02.
- [8] Chang Siqin. Automobile Power Plant [M]. Beijing: China Machine Press, 2006. 180-181.
- [9] Xia Jingjing, Li Chunliang. Velocity Control of CVT Automotive Based on Engine Brake [J]. Machine Tool & Hydraulics 2011, 39 (17): 33-36.
- [10] Liu Tianhao, Zhang Xueliang. The Co-simulation Study of Hydrostatic CVT [J]. Machine Tool & Hydraulics 2010, 38(19): 97-1