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Research paper

Simulation and experimental study on the pump efficiency improvement of continuously variable transmission

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ABSTRACT

To reduce the power loss of a pump in continuously variable transmission (CVT), a new hydraulic scheme is proposed. This new scheme adjusts the effective displacement of the pump by using lubrication pressure and controls the pressure of primary and secondary cylinders through the smart mode. The power matching model of the new hydraulic scheme is established. The models of hydraulic system, vehicle and transmission control unit are built. A closed loop is formed to place the software in loop simulation through Silver virtual integration platform. The simulation results show that the new hydraulic scheme can match the power demand well. In NEDC, the hydraulic efficiency of the new hydraulic scheme can increase by 24.7% and 23.6% compared with those in the quantitative and single pumps, respectively, the fuel consumption of the new hydraulic scheme can reduce 3% and 4.1% compared with those in the single and quantitative pumps. Finally, the new hydraulic scheme is verified through the bench test, which reveals that the variable pump of the new hydraulic scheme can considerably reduce the torque loss of the pump, the smart mode can improve the transmission efficiency of CVT by up to a maximum rate of 3.17%.

1. Introduction

Continuously variable transmission (CVT) can change the speed ratio automatically at a certain range depending on the driving conditions of a vehicle; thus, CVT leads to the best fuel economy curve of the engine during operation and reduces the vehicle's fuel consumption rate [1–3]. However, the fuel economy of a vehicle equipped with CVT does not reach the expected target because of the low efficiency of this transmission. The transmission efficiency of CVT is in the range of 75%–90% [4,5]. Therefore, many scholars have studied how to improve the CVT's transmission efficiency. Adachi et al. [6,7] improved the fuel efficiency of engines by optimising the CVT speed ratio controller to track the target speed ratio accurately, but this strategy only slightly decreased the fuel consumption rate [8,9]. Van et al. [10–12] optimised the clamping force controller through the methods of extreme search or slip rate control, which reduced maximally the clamping force between the metal belt and the pulleys or reduced the friction loss between the metal belt and the pulleys when the belt did not slip. Akehurst et al. [13–18] diminished the mechanical friction loss of CVT by analysing and optimising the deformation and the friction coefficient between pulleys and the conveyor belt. Bertini et al. [19] analysed the power loss model

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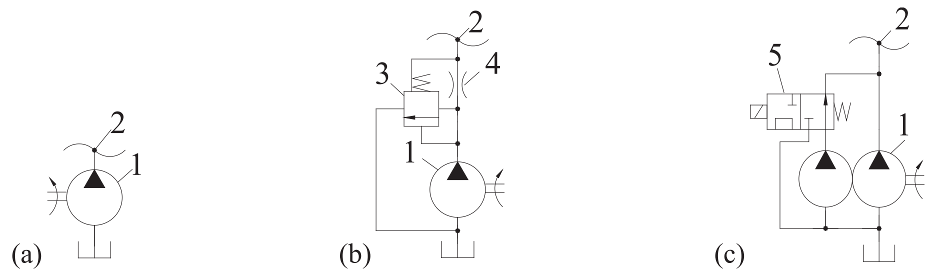

Fig. 1. Oil supply schemes of CVT's traditional hydraulic system. (a) Single pump, (b) quantitative pump and (c) double-joint pump. 1, Single pump or double pump. 2, Hydraulic valve body. 3, Constant flow valve. 4, Orifice. 5, High-speed on-off valve.

of rubber belt CVT. The authors attributed the power loss of CVT to the sliding friction amongst the rubber belt and pulleys, the internal hysteresis of rubber and friction. In the total power loss of CVT, the speed change mechanism accounted for only about 30%, whereas the power loss of pump accounted for 42% [20]. Therefore, reducing the power loss of pump in CVT can greatly reduce the fuel consumption of a vehicle. Few scholars have analysed how to reduce the efficiency loss of the CVT pump. Van et al. [21] proposed that the CVT's hydraulic system can be designed as an independent circuit that applies the smart mode and uses the auxiliary electric pump to reduce the power loss of pump, but they did not show an in-depth demonstration of the scheme. Bradley et al. [22] used a servo pump to control the pressure and flow of CVT and found that the system increases the fuel consumption rate by 5%. However, it remained difficult to industrialise because of its high cost. Seonwoo et al. [23] reduced the power loss of pump by optimising the structure of vane pump and by increasing the pump mechanical and volumetric efficiency.

The present study analyses how to improve the transmission efficiency of CVT's hydraulic system from the perspective of industrialisation. Firstly, on the basis of comparison of the disadvantages of single pump, quantitative pump and double-joint pump schemes, a new hydraulic scheme is proposed. This new scheme adjusts the effective displacement of pump using the CVT lubrication pressure and controls the pressure of the primary and secondary cylinders through the smart mode. Secondly, the power matching mathematical model of the hydraulic scheme is established. Then, the simulation models of the vehicle, transmission control unit (TCU) and hydraulic system are built and form a closed loop on the basis of the Silver virtual integration platform, thereby placing the software in loop simulation. The power matching comparison of single pump, quantitative pump and the new hydraulic scheme is carried out under the conditions of full throttle launching, rapid acceleration and NEDC. Finally, the variable pump and the smart mode of the new hydraulic scheme are verified through the bench test.

2. Oil supply schemes for CVT

At present, the main oil supply schemes of CVT's hydraulic system are the single, the quantitative and the double-joint pumps (Fig. 1.(a)–(c)). The entire flow from the single pump passes through the hydraulic valve body, which produces substantial overflow loss of the pump at high engine speed. The flow of the quantitative pump to the hydraulic valve body is adjusted by a constant flow valve and an orifice, which maintains an almost constant value of the maximum flow to the hydraulic valve body. However, the orifice produces pressure loss. The working pressure of pump is greater than the maximum pressure need of the hydraulic system, and the excess flow is relieved to the tank. Therefore, the power loss of the pump is not reduced. The hydraulic efficiencies of the single pump and the quantitative pump are low. Thus, their industrialisation will lead to higher fuel consumption of automobiles. The flow of the double-joint pump to the hydraulic valve body is controlled by the high-speed on-off valve according to the flow demand of hydraulic system. Although the double-joint pump can improve the hydraulic efficiency of pump obviously, its industrialisation is difficult because of the high cost of high-speed on-off valve. Moreover, the control strategy of high-speed on-off valve is complex, and the calibration work of it is difficult, thereby generating additional development cost. Considering the high cost and high fuel consumption of above-mentioned schemes, this paper presents a new hydraulic scheme, in which the effective displacement of the pump is regulated by lubrication pressure and the pressures of the primary and secondary cylinders are controlled under the smart mode.

In order to reduce the flow loss of the pump, a variable pump of the new hydraulic scheme is proposed which combines a double-acting vane pump, a one-way valve and a hydraulically controlled directional valve, as shown by the dotted box in Fig. 2. The hydraulically controlled directional valve is regulated by lubrication pressure. Thus, the flow of the pump into the hydraulic valve body is controlled. The working principle of the hydraulically controlled directional valve will be elucidated in the third part. The CVT's hydraulic system should satisfy the pressure and the flow requirement of the secondary cylinder, primary cylinder and clutch, which is usually placed in auxiliary circuit first. The excess flow overflows to the lubricant circuit by the fixed value relief valve. A larger excess flow results in greater lubrication pressure. Therefore, the lubrication pressure can reflect the demand flow of the CVT's hydraulic system to the pump.