Reverse design and characteristic study of multi-range HMCVT

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Abstract. The reduction of fuel consumption and increase of transmission efficiency is one of the key problems of the agricultural machinery. Many promising technologies such as hydro-mechanical continuously variable transmissions (HMCVT) are the focus of research and investments, but there is little technical documentation that describes the design principle and presents the design parameters. This paper presents the design idea and characteristic study of HMCVT, in order to find out the suitable scheme for the big horsepower tractors. Analyzed the kinematics and dynamics of a large horsepower tractor, according to the characteristic parameters, a hydro-mechanical continuously variable transmission has been designed. Compared with the experimental curves and theoretical curves of the stepless speed regulation of transmission, the experimental result illustrates the rationality of the design scheme.

1 General instructions
Since the emergence of power-split transmissions in agricultural tractor, the presence of this type of transmissions has been increasing. These kinds of transmissions have been well received by farmers because of their obvious advantages, such as ease of handing and response to the requirement. Nevertheless, there is not a systematic theory to study them, which is a disadvantage in presenting the characteristics and design ideas.

Hydro-mechanical continuously variable transmissions were installed in tractors beginning in 1996. Fendt’s VARIO was surprising because of its originality. In 2000, Steyr-Case’s S-MATIC arrived at a series production, followed by ZF and John Deere’s “Auto Power”; all of them have input coupled planetary types with 4 or 5 shafts. Renius [1] provided a comprehensive overview of the hydro-mechanical continuously variable transmissions and analyzed the efficiency of two classical types: input coupled planetary and output coupled planetary. Orshansky and Kireieczyk [2] analyzed and simulated the hydro-mechanical continuously variable transmissions with 3 planetary gears. Linares explained the design parameters for hydro-mechanical continuously variable transmissions using planetaries with 3 active shafts.

Taking the CVT of crawler tractors as research object, this paper designs a hydro-mechanical continuously variable transmission with a double planetary gear and analyses the transmission characteristics.

2 Design scheme of HMCVT

2.1 Analysis of kinematics and dynamics
The reference vehicle for transmission study is a big horsepower tractor, the mathematical model of tractor speed can be described as follows:
The relevant parameters can be expressed as follows: maximum output power of engine is $P_e=120$ (kW), rated speed of engine is $n_{emax}=2300$ (r/min), maximum torque of engine is $T_{emax}=600$ (Nm); tractor speed scope is $v \in [10,30]$ (km/h); tractor driving wheel slip ratio scope is $\delta \in [0.03,0.14]$, we can take $\delta=0.07$; tractor mass is $m=8000$ (kg), tractor wheel power radius is $r_q=0.350$ (m); transmission ratio of main reducer scope is $i_0 \in [3,5]$, we can take $i_0=4$; transmission ratio of hub reduction gear scope is $i_{hr} \in [3,6]$, we can take $i_{hr}=5.6$.

Ignoring the acceleration resistance and the air resistance, the tangential traction of tractor $F_{t,max}$ should be greater than the resistance of full load at the max slope pavement $\sum F_{t,max}$.

$$F_{t,max} \geq \sum F_{t,max} = G \cos \alpha_{max} f + G \sin \alpha_{max}$$

(2)

Where $G$ is full-load mass of tractor (N), $\alpha_{max}$ is maximum climbing degree, $f$ is rolling resistance coefficient.

The tractor should also meet that the tangential traction traction $F_{t,run}$ is not greater than the adhesion $F_\phi$, that is:

$$F_{t,run} \leq F_\phi = \varphi G$$

(3)

Where $\varphi$ is adhesion coefficient.

Through the analysis of experimental data, the maximum climbing degree of tractor in farmland and clay soil are both 37°, in sandy soil, meadow and mud are respectively 25°, 18° and 12°.

2.2 Structure of HMCVT

The structure diagram of HMCVT is shown in Fig.1. The front ring gear and back planet carrier of the double planetary gear are respectively connected with the front and back hydro-mechanical output shaft. By the engagement of clutches in the intermediate shaft, the power output from the output shaft. The hydraulic clutches are controlled by the the electromagnetic reversing valve. Starting and braking is the hydraulic range, which is controlled by clutch $C_1$, and the hydro-mechanical ranges are controlled by the rest of the clutches.

![Figure 1. Structure diagram of HMCVT](image-url)
Table 1. Clutches engagement status of HMCVT

| Ranges  | C1                  | C2 | C3 | C4 | C5 |
|---------|---------------------|----|----|----|----|
| Forward | F1(N)               |    |    |    |    |
|         | F2(P)               |    |    |    |    |
|         | F1(N)               |    |    |    |    |
|         | F1(P)               |    |    |    |    |
|         | F(H)                |    |    |    |    |
| Reverse | R1(E)               |    |    |    |    |
|         | R1(P)               |    |    |    |    |
|         | R1(N)               |    |    |    |    |

Note: “●” represents the engagement status.

3 Parameter design of HMCVT

3.1 Parameters of hydraulic components

Series 90 axial piston pump and motor (055HDC) are selected as the main hydraulic components, the main parameters are shown as follows: pump/motor rated speed is $n_{P_{max}}/n_{M_{max}}=3900(\text{r/min})$, pump/motor rated displacement is $D_{P_{max}}/D_{M_{max}}=55(\text{cm}^3/\text{r})$, pump/motor rated pressure is $p_{P_{max}}/p_{M_{max}}=420(\text{bar})$.

Hydraulic component selected should satisfy Equation (4):

$$P_{P_{max}} = \frac{Q_{r_{max}} \Delta p_{max}}{600 \eta_p} \geq P_{e_{max}}$$

Where $P_{P_{max}}$ is the maximum output power of pump (kW), $Q_{r_{max}}$ is the maximum displacement of pump(L/min), $\Delta p_{max}$ is the maximum pressure of system(bar), $\eta_p$ is the total efficiency of pump.

Through the analysis of the products above, the following conclusions can be drawn:

1. The efficiency of pump and motor has a close association with the displacement, speed and pressure. The volumetric efficiency and mechanical efficiency of hydraulic system are reduced with usage time. This paper assumes the volumetric efficiency of pump and motor are both 94%.

2. The input torque of pump should be less than 381.2N·m, the pump speed scope is $560 \sim 3900 \text{r/min}$; The output torque of motor should be less than 354.6N·m, the motor speed scope is $500 \sim 3490 \text{r/min}$.

3. Consider comprehensively the influence of pressure, temperature and air to the hydraulic system, the optimal condition of hydraulic system is the medium pressure and relatively higher speed.

3.2 Transmission ratios of ranges

The transmission ratios of ranges for the multi-range HMCVT are shown in table 2.

Table 2. Transmission ratios of ranges

| Range   | Transmission ratio | Range   | Transmission ratio |
|---------|--------------------|---------|--------------------|
| F2(N)   | $i_g = \frac{k_2 k_3 k_4 l_5}{l_2 + s \eta_p}$ | F2(P)   | $i_g = \frac{(k_2 + 1) l_4 l_5}{k_3 + s \eta_p}$ |
| F1(N)   | $i_g = \frac{k_2 k_1 l_2 l_3}{l_2 + s \eta_p}$ | F1(P)   | $i_g = \frac{(k_2 + 1) l_4 l_5}{k_3 + s \eta_p}$ |
| F(H)    | $i_g = \frac{l_2 + s \eta_p}{s \eta_p}$        | R1(E)   | $i_g = \frac{l_2 + s \eta_p}{s \eta_p}$        |
| R1(P)   | $i_g = \frac{(k_2 + 1) l_4 l_5}{l_2 + s \eta_p}$ | R1(N)   | $i_g = \frac{k_3 l_4 l_5}{l_2 + s \eta_p}$    |
3.3 Parameters of transmission ratios

Engine power is directly transferred to the pump:

\[
\begin{align*}
\frac{n_{p, \text{max}}}{i_4} & \leq n_{p, \text{max}} \\
T_{\text{max}}i_4 & \leq T_{p, \text{max}}
\end{align*}
\]

(5)

According to the calculation result, \( i_4 \in [0.59, 0.63] \), we can take \( i_4 = 0.62 \). The maximum speed of hydraulic range generally doesn’t exceed the 20% of the top speed. Taking into account the service life of hydraulic units, this paper assumes that the top speed of hydraulic starting range is 2 km/h, so the common ratio of 4 range geometric type HMCVT is 1.97.

According to Equation (1) and the characteristic parameters of tractor, \( i_e \in [-\infty, -1.26] \cup [0.42, 0.6, 3.00] \). A stable synchronized shifting should meet the same transmission ratio and displacement ratio when shifting.

3.4 Starting and braking check

1. Hydraulic range can drive vehicle’s starting, that is:

\[
\begin{align*}
\nu_H = 0.377(1 - \delta) \frac{n_{M, \text{max}}l_q}{i_kl_kh_Li_B} & \geq 20\%v_{\text{max}} \\
T_{M, \text{max}}l_2l_3l_4h_Lh_{LB} & \geq G\rho q_y
\end{align*}
\]

(6)

Where \( \nu_H \) is the speed of hydraulic range (km/h), \( v_{\text{max}} \) is the maximum speed of tractor (km/h); transmission efficiency of main reducer can be regarded as \( \eta = 0.9 \); transmission efficiency of hub reduction gear range can be regarded as \( \eta_{LB} = 0.9 \).

2. Hydraulic range can also provide the braking torque:

\[
T_{M, \text{max}}\eta_{LB} & \geq \frac{Z\rho q_y}{i_kl_kh_Li_B}
\]

(7)

Where \( z \) is the severity of braking. According to the analysis above, the transmission ratios of the ordinary gears are presented as follows: \( i_1 = 1.21 \), \( i_2 = 1.00 \), \( i_3 = 1.21 \), \( i_4 = 0.62 \), \( i_5 = 1.42 \), \( i_6 = 1.90 \), \( i_7 = i_8 = 1.98 \), \( i_9 = i_{10} = 0.51 \), \( i_{11} = 1.39 \), \( i_{12} = 1.24 \).

3.5 Clutch parameters

This paper selects the wet clutches to realize the shifting. Complete engagement and separation of the external hub and internal hub of the clutches through the control oil pressure. The external hub and gears are connected by bolts, and the internal hub and shaft are connected by the double flat key. The sliding bearing and the needle bearing share the cooling and lubricating system, which adopts the pressure lubrication, while other gears in the transmission system adopt the splash lubrication, the hydraulic system of clutches is presented in Fig.2.

![Figure 2. The hydraulic system of clutches](Image)
According to top speed, maximum torque and the parameters of transmission ratios, the limiting speed and torque the clutches can bear are presented in Tab.3.

| Clutches | Speed (r/min) | Torque (Nm) |
|----------|---------------|-------------|
| C₁       | 1294          | 957         |
| C₂       | 722           | 3768        |
| C₃       | 1409          | 1497        |
| C₄       | 2802          | 971         |
| C₈       | 5464          | 498         |

4 Speed regulating characteristic analysis

4.1 Test bench of HMCVT

The test bench of hydro-mechanical continuously variable transmissions is composed of the mechanical part and the control part. The mechanical part includes diesel engine, torque and speed sensors, HMCVT and oil tank. The control part based on the virtual instrument software developing platform LabVIEW ensures the precise control of shifting clutches and pump control motor system, and set up the microprocessor system to conduct analysis on the information collected on the site, put forward the test report and make timely feedback to the test system.

4.2 Speed characteristic analysis

According to the transmission ratios of ranges for the multi-range HMCVT are shown in table.2, Fig.3 presents the relation curves of transmission ratios and displacement ratio, which can show the stepless speed regulating characteristic of HMCVT.

The engine uses the idle mode, in order to stabilize the speed. When the engine speed is 1000r/min, 1500r/min and 2000r/min in three cases and the relationship between speed and displacement ratio are shown in Fig.4.

Figure 3. Relation curves of transmission ratios and displacement ratio
(1) The tractor can realize stepless speed change for the different speeds of engine. The results agree well with the values measured experimentally in the lower range, the error is larger in the hydraulic range for the lower efficiency of hydraulic system. The higher speed of the engine, the fluctuation is more obvious in the higer range, which is caused by the speed regulating characteristic of the engine.

(2) When the engine is operating in the lower speed and the transmission is regulated to the lower range, the stepless speed stability and continuous response are great. When the engine is operating in the higher speed and the transmission is regulated to the medium range, the system characteristic can achieve the optimal state.

(3) The wide scope of transmission ratios of the lower range is conductive to the low speed characteristic of the tractor, which can select the suitable operation mode for different load. The change of the speed of tractor is obvious with the change of displacement ratio of the higher range, which is conductive to the transport operations.

5 Conclusions
This paper presents the design idea of HMCVT, the design parameter of HMCVT can be obtained through the analysis of kinematics and dynamics for the big horsepower tractor, including parameters of hydraulic components, transmission ratios of ranges, parameters of transmission ratios, clutch parameters, and so on. Compared with the experimental curves and theoretical curves of the stepless speed regulation of transmission, the experimental result illustrates the rationality of the design scheme.

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