Design and analysis of automatic transmission for Ravigneaux transmission with four speed

Xiaoyan Song*
Department of transportation and mechanical engineering Shenyang Urban Construction University Shenyang, China
*sxy@syucu.edu.cn

Abstract—The automatic transmission can automatically choose the gear according to the engine condition and the running speed of the car. In this paper, according to the structure characteristics of planetary gear mechanism, the different combination of shift actuators, get the movement rule and working principle of each gear position, calculated the specific parameters of each row of planetary gear mechanism. Next the article take Ravigneaux type of four gear automatic transmission for example, complete the design of automatic gearbox transmission mechanism, include various gear transmission route and the transmission scheme design, finally through the concrete parameters, finish the structure design of the whole planetary gear transmission part.

1. INTRODUCTION
The core of automatic transmission is to realize automatic shift, so that the vehicle starts more smoothly, and improve the ride comfort greatly. In contrast to the manual transmission, the automatic transmission replaces the traditional clutch with a hydraulic torque converter, which connects the engine to the transmission system for power transfer, allowing the driver to control the speed simply by using the accelerator pedal. In addition, hydraulic transmission has a certain damping performance, can extend the service life of the transmission system, so the automatic transmission in the vehicle has been widely developed and applied.

2. AUTOMATIC TRANSMISSION STRUCTURE AND PRINCIPLE
The automatic transmission is mainly composed of hydraulic torque converter, transmission mechanism, shift actuators, hydraulic control system and electronic control system.

2.1. Hydraulic torque converter
Hydraulic torque converter with hydraulic oil as the working medium, hydraulic torque converter is a hydraulic oil(ATF)transfer power device, its structure includes pump wheel, turbine, guide wheel three components, installed between the engine and transmission, transmission torque, change speed and clutch role.

The pump wheel is the input element of the power. When the input shaft rotates, the pump wheel is driven to rotate together. The liquid flows out through the pump wheel blade, passes through the turbine, the guide wheel returns to the pump wheel. The torque converter transfers torque by the interaction between the liquid and the blades. In the process of liquid circulation, the fixed guide wheel gives a reaction torque to the turbine, so that the output torque of the turbine is different from the input torque of the pump wheel, so it has the function of "torque converter".
2.2. Transmission mechanism
To further increase the torque, enlarge its range of variable speed, improve the adaptability of the car, a driving mechanism is arranged behind the hydraulic torque converter. At present, planetary gear mechanism is often used, it mainly consists of solar wheel, gear ring, planetary rack and planetary gear. Through different components to be active and limited by the action of different components to realize variable speed control. In the process of speed ratio change, the whole planetary gear group still exists motion, power transmission is not interrupted, so the power shift is realized. Automatic transmission is generally composed of two to four planetary gear transmission mechanism.

2.2.1. Introduction of planetary gear structure
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2.2.1.1. Introduction of planetary gear structure.
There are many types of planetary gear mechanism, one of the simplest planetary gear mechanism components mainly consists of a planetary shelf, several planetary gears, a gear ring and a sun wheel. The central gear of the planetary gear mechanism is the sun wheel, and the planetary gear is installed on the planetary shelf. It is required to arrange the planetary gear symmetrically between the sun wheel and the gear ring, as shown in figure 1. The sun wheel, gear ring and the planetary shelf have a common axis of rotation. The planetary gear is supported on the planetary gear shaft fixed on the planetary shelf and meshes with the sun wheel and gear ring at the same time.

![Figure 1. Schematic diagram of planetary gear structure](image)

2.2.1.2. The principle of speed change of a planetary gear mechanism.
Any member of the sun wheel, Gear ring and planetary shelf is connected to the drive shaft, the second component is connected to the driven shaft, the third component are forced to fixed or the motion is constrained, such as set the speed of the components to a certain value, the whole system transfers power at a certain transmission ratio, so realize the different gear speed. See table I for details.

| Fixed part     | Drive part      | Drived part    | Transmission ratio | Speed       | Rotation direction |
|----------------|-----------------|----------------|--------------------|-------------|--------------------|
| Gear ring      | Sun wheel       | Planetary shelf| 2.5-5              | Deceleration| Same               |
| Gear ring      | Planetary shelf | Sun wheel      | 0.2-0.4            | Acceleration| Same               |
| Sun wheel      | Gear ring       | Planetary shelf| 1.2-1.6            | Deceleration| Same               |
| Sun wheel      | Planetary shelf | Gear ring      | 0.6-0.8            | Acceleration| Same               |
| Planetary shelf| Sun wheel       | Gear ring      | 1.5-4              | Deceleration| Contrary           |
Modern auto transmission is consisted by 2 to 4 planetary gear transmission mechanism generally. There are two typical forms of structure, Simpson type planetary gear transmission mechanism and ravigneaux type planetary gear transmission mechanism.

Simpson type planetary gear drive mechanism mainly consists of two planetary rows with identical structural parameters. Its structure characteristics are: before and after the two planets platoon share a sun wheel, which is called front and rear sun gear. The planetary rack of the front planetary row is connected with the inner gear ring of the rear planetary row as the output shaft of the automatic transmission; The inner ring of the front planetary bank and the solar wheel assembly are usually used as input shafts for the automatic transmission. Simpson-type planetary gear mechanism combined with different number of gear shifting actuators can constitute a three-or four-gear planetary gear transmission system.

Ravigneaux type planetary gear mechanism consists of a single row single stage planetary gear mechanism and a single row double stage planetary gear mechanism. The structure features are as follows: the front row is a single-stage planetary gear mechanism, and the back row is a double-stage planetary gear mechanism. The front and back rows share a planetary shelf and an inner ring. The front solar wheel is called the large solar wheel, meshing with the rear planetary gear; The rear solar wheel is called the small solar wheel and meshes with the short planetary gear.

### 2.2.1.3. Design of planetary gear mechanism.

#### Design of gear ring parameter

First determine the basic parameters, transverse module is $m_s = 1.5$, Gear ring indexing circle diameter is $D = 132 \text{mm}$, the pressure Angle is the standard value $\alpha_s = 20^\circ$, so the normal modulus is $m = \frac{m_s}{\cos \beta} = \frac{1.5}{\cos 25^\circ} = 1.655$. For helical drives, the larger the helical angle, the more inclined the gear teeth, the better the transmission stability, usually take $\beta = 8^\circ \sim 25^\circ$, this design helical gear helical angle $\beta = 25^\circ$. Then the number of tooth ring teeth is $Z = \frac{d}{m} = \frac{132}{1.655} = 79.75$, after rounding, then $Z = 80$.

Design of sun wheel: Take the transmission ratio of each gear as $i_1 = 2.632, i_2 = 1.556, i_1 = 1, i_2 = 0.712$. According to the first gear ratio calculation, the characteristic parameters of the rear planetary row is $\alpha_2 = i_1$, Then the number of gear teeth for small sun gear is $Z_2 = \frac{Z_1}{i_2} = \frac{80}{2.632} = 30.39$, after take integer, then $Z_2 = 30$.

According to the second gear ratio calculation, the characteristic parameters of the rear planetary row is $\alpha_1 = 1.971$, Then the number of gear teeth for large sun gear is $Z_3 = \frac{Z_2}{\alpha_1} = \frac{80}{1.971} = 40.58$, after rounding, then $Z_3 = 40$.

Concentric Condition: In planetary transmission mechanism, in order to improve its bearing capacity, several planetary wheels are mostly adopted to evenly distribute the planetary wheels on the same circumference of the transmission. The number of planetary wheels ranges from 3 to 6. Take 3 Gear ring, that is $n_s = 3$. It consists of three long planetary wheels and three short planetary wheels. The
number of long planetary wheel is \( Z = \frac{1}{2}(Z_1 - Z_2) = \frac{1}{2}(80 - 40) = 20 \). Refer to mechanical design manual for short planetary gear number: \( Z_n = 19 \).

3. Shift Actuators
Shift actuators are used to change the active element in the planetary gear or limit the movement of a component, change the direction of power transmission and speed ratio, mainly composed of multi-disc clutch, brake and one-way clutch. The purpose of the clutch is to transfer power to one of the elements of the planetary gear mechanism to make it the driving part. The function of the brake is to hold one of the elements in the planetary gear mechanism so that it does not move. One-way clutch is also a planetary gear transmission shifting element, its role and the multi-disc clutch and brake are basically the same, is also used to fix or connect several planetary row in some sun wheel, planetary rack, gear ring and other basic components, so that the planetary gear transmission formed a different transmission ratio of the block.

The structure of the shift actuator designed in this paper is relatively simple. There are only three clutches \( (C_1, C_2, C_3) \), two brakes \( (B_1, B_2) \) and one one-way clutch \( (F_1) \), Locking clutch \( (C_0) \). The transmission can realize four speed transmission. The specific structure is shown in Figure 2.

3.1. Shift transmission line
- First gear: clutch \( C_1 \) is engaged, one-way clutch \( F \) works, so the Gear ring can only rotate clockwise, the planetary shelf is braked, and the small sun wheel is connected with the input shaft. At this time, the transmission route is as follows: pump wheel → guide wheel → turbine → clutch \( C_1 \) → small sun wheel → short planet wheel → long planet wheel, finally output through gear ring.
- Second gear: clutch \( C_1 \) engaged, brake \( B_2 \) brake the big sun wheel. Power transmission Route as follow: the large sun wheel is not moving, the pump wheel → guide wheel → turbine → turbine shaft → clutch \( C_1 \) → small sun wheel → short planet wheel → long planet wheel, finally output through the gear ring.
- Third gear (direct gear): Locking clutch \( C_0 \) engaged, hydraulic torque converter is locked, clutch \( C_1, C_2, C_3 \) engaged, planetary gear drive mechanism is locked, So the whole planetary gear mechanism turns as one machine. Power transmission route is: pump wheel → lock clutch → whole planetary gear pair, and finally output power.
- Fourth gear (overdrive): Locking clutch \( C_0 \) is locked, clutch \( C_3 \) engagement, brake \( B_2 \) brake the big sun wheel. Power transmission route is: pump wheel → lock clutch \( C_0 \) → clutch \( C_3 \) → planetary rack → long planetary wheel, and finally output power through gear ring.
- Reverse gear: reverse clutch \( C_2 \) engagement, big sun wheel rotation. Brake \( B_1 \) works. So that the planetary frame is braked. At this time, The power transmission route is as follows: pump wheel → guide wheel → turbine → turbo shaft → clutch \( C_2 \) → large sun wheel → long planet wheel, and finally, the gear ring is driven in reverse to transfer power.
Neutral gear: all clutches and brakes are in idle state. At this time, all parts of the planetary gear mechanism can move freely, so the planetary gear mechanism does not transmit power and the transmission is in the position of empty (N) block.

The combination of the structures in the work is summarized in table II.

3.2. The design of clutch \(C_1\)

The main role of clutch \(C_1\) is to connect the intermediate shaft with the front planetary gear ring, it is connected to the input shaft by an involute spline, the friction plate is connected to the coupling drum, which in turn is connected to the small sun wheel by splines. Include clutch drum 5, friction plate 10, steel plate 9, return spring (helical spring) 6, piston 3, clasp 1, spring seat 2, o-ring, disc spring 7, pressure plate 10, etc. The specific structure is shown in figure 3.

![Figure 3. Decomposition diagram of clutch](image)

3.2.1. The design of friction plate size and spline

In the clutch, the friction plates and the steel plates are arranged in contact with each other. When they work, they are squeezed with each other to form friction, so as to realize the predetermined function. The difference between contact surface is coated with a layer of copper-based powder metallurgy material. The outer diameter of friction plate \(-D(m)\) is calculated, according to the maximum torque \(-T_{e \max}(N \cdot m)\) of engine, Calculation formula is

\[ D = 100 \sqrt{\frac{T_{e \max}}{A}} \]  

Take \(A = 47\). Take the maximum torque \(T_{e \max} = 172 N \cdot m\), It is calculated that \(D = 191.3 mm\). According to the standard series size of friction plate, take outer diameter \(D_i = 200 mm\), internal diameter \(d_i = 140 mm\), so the large diameter of internal spline is \(D_{sp} = 140 mm\), thickness is \(b = 3.5 mm\), \(c = 0.700\).

### TABLE 2. The working condition of any shift actuators under all gears

| Joystick | Gear shift   | Clutch | Brake | One-way clutch |
|----------|--------------|--------|-------|----------------|
|          |              | \(C_1\) | \(C_2\) | \(C_3\) | \(B_1\) | \(B_2\) | \(F\) |
| P        | Parking gear | ○      |       |     |          |       |  |
| N        | Neutral gear | ○      |       |     |          |       |  |
| D        | 1            | ●      | ●     | ●   | ●        |       |  |
|          | 2            | ●      | ●     | ●   | ●        |       |  |
|          | 3            | ●      | ●     | ●   | ●        |       |  |
|          | 4            | ●      | ●     | ●   | ●        |       |  |
| R        | Reverse gear | ●      | ●     | ●   |          |       |  |

Remarks: ● Indicates connection and transfer power, ○ Indicates connection but do not transfer power.
According to national standard GB/T3478.1-2008, take $m = 2.5$. Because $D = m(Z + 1.5)$, then by calculation, we can get $Z = 54.5$. We take integer $Z = 50$. Index circle diameter $D = mZ = 2.5 \times 50 = 125 \text{mm}$, Small diameter of internal spline $D_i = D - 1.25m = 136.875 \text{mm}$, take integer $D_i = 136 \text{mm}$, gear thickness $S = 0.5m = 3.925 \text{mm}$, Thickness of friction plate $h = 3.5 \text{mm}$. Select cylindrical straight involute spline with $30^\circ$ flat root. Strength checking calculation of spline connection: as it is a dynamic connection, it is checked by the following methods:

$$p = \frac{2T \times 10^3}{\phi Z h l d_m} \leq [P]$$

\(T\) — Torque, \(T = 172 \text{Nm}\); \(\phi\) — Load nonuniformity coefficient, \(\phi = 0.7\); \(Z\) — Spline tooth number, \(Z = 50\); \(l\) — Working length of gear teeth, \(l = 2.5 \text{mm}\); \(h\) — Working height of gear teeth, take \(h = m = 2.5\); \(d_m\) — Average diameter. For involute spline, take the diameter of graduation circle $d_m = 125$.

### 3.2.2. The design of clutch C2 and C3.

The friction plate selected for clutch C2 and C3 is the same as clutch C1. For the specific design process, see the design steps of clutch C1. The return spring is also a spiral spring.

### 3.2.3. The design of brake B1

This design adopts disc brake. The disc brake B1 is used to brake the planetary shelf. B1 is connected with the automatic transmission housing through the external spline of the steel plate, and connected with the planetary shelf through the internal spline of the friction plate. The brake realizes the braking of planet carrier by braking the friction element. Brake B1 uses the centrifugal force generated by the rotation of the planetary mechanism to throw the brake fluid out of the oil chamber. The main parts of brake B1 are brake drum, brake pressure plate, friction element, piston, etc. As for the selection of friction components, refer to the design process of clutch C1. Here, only the basic dimensions of friction components are calculated.

#### 3.2.3.1. Calculation For torque capacity

The calculation method of torque capacity is:

$$T_{B1} = \beta T_{\text{max}} = P \mu_s R n K = \frac{\pi f_k n^2}{12} - q_0 D_i^2 (1 - C^3) \phi K$$

\(T_{B1}\) - torque, \(T_{\text{max}} = 172 \text{Nm}\); \(\beta\) - Reserve coefficient, take \(\beta = 1.2\); \(T_{\text{max}}\) - Rated torque, \(T_{\text{max}} = 146 \text{Nm}\); \(P\) - pressure force, \(P = 2.8 \text{KN}\); \(\mu_s\) - Coefficient of dynamic friction of friction liner, \(\mu_s = 0.09\); \(n\) - Number of friction surfaces, \(n = 2 \times Z_f = 10\), \(Z_f\) is the number of friction patches; \(q_0\) - Friction plate specific pressure; Allowable specific pressure of friction plate \(q_0 = 0.5 \text{MPa}\); \(\phi\) - The ratio of net area to friction lining area, calculated $\phi = 0.21$; \(K\) - Pressure loss coefficient, take $K = 0.95$. \(D_i\) - External diameter of friction plate, According to the structure size preliminary select $D_i = 156 \text{mm}$; \(D_2\) - Inner diameter of friction plate, preliminary select $D_2 = 184$; \(C\) - Ratio of internal and external diameters of friction plates, \(C = \frac{D_2}{D_i} = 0.84\).

#### 3.2.3.2. The design of friction plate size and spline

The involute spline of cylindrical straight tooth with $30^\circ$ square root is used for this spline, According to the radial dimension of the transmission, it take external diameter of friction plate preliminary $D_o = 178 \text{mm}$, inner diameter $d_i = 150 \text{mm}$. Then the large diameter of internal spline is
\[ D_p = 150 \text{mm} \]. According to GB/T3478.1-2008, it can take \( m = 4 \), because \( D_p = m(Z + 1.5) \), \( Z = 36 \), by calculation, we get \( D = mZ = 4 \times 36 = 144 \text{mm} \).

\[ D_s = D_p - 1.25m = 145 \text{mm}, \quad S = 0.5m = 6.28 \text{mm}, \quad h = 4 \text{mm}. \]

### 3.2.3.3. The design of steel and spline

Steel thickness is 4 mm, internal diameter \( D_i = 136 \text{mm} \), external diameter \( D_e = 151 \text{mm} \). Small diameter of external spline is \( D_s = 151 \text{mm} \). According to GB/T3478. 1—2008, it can take \( m = 4 \), because \( D = m(Z - 1.5) \), so by calculation, we get \( Z = 39.25 \), Round numbers, take \( Z = 36 \), Index circle diameter \( D = mZ = 4 \times 36 = 144 \text{mm} \), \( S = 0.5m = 6.28 \text{mm} \).

### 3.2.4. The design of brake B2

Brake B2 is used to brake the big sun wheel. The internal spline on the brake drum is combined with the external spline of the big sun wheel, and the big sun wheel is braked by tensioning and loosening the brake belt. Its design method is the same as that of brake B1.

### 3.2.5. One-way clutch

The one-way clutch F is used to brake the planet carrier and prevent it from turning in the opposite direction. The outer ring is integrated with the planetary shelf, and the inner ring is sleeved on the piston of brake B2. When the Planetary shelf rotates reversely with the piston of brake B2, the wedge block is stuck, which prevents the planet carrier from rotating reversely.

### 4. Conclusions

In this study, we established the main structure of automatic transmission design. planetary gear structure. Including planetary gear transmission mechanism of planetary gear, sun wheel, gear ring, gear shift actuator clutch, brake and so on.

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